Supplementary publications / Carnegie Institution of Washington
Washington, D.C. : Division of Publications, Carnegie Institution of Washington

https://hdl.handle.net/2027/umn.31951p01105529v

Creative Commons Zero (CC0)
http://www.hathitrust.org/access_use#cc-zero

This work has been dedicated by the rights holder to the public domain. It is not protected by copyright and may be reproduced and distributed freely without permission. For details, see the full license deed at http://creativecommons.org/publicdomain/zero/1.0/.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero

SUPPLEMENTARY
PUBLICATIONS
(CARNEGIE INSTITUTION
OF WASHINGTON)

MAGNETIC FIELD OF THE EARTH AND ITS ATMOSPHERE

5

1932

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero

Digitized by Google

Original from
UNIVERSITY OF MINNESOTA

Twin Cities Campus

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero

Digitized by Google

Original from
UNIVERSITY OF MINNESOTA

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero

Digitized by Google

Original from
UNIVERSITY OF MINNESOTA

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero

Digitized by Google

Original from
UNIVERSITY OF MINNESOTA

CARNEGIE INSTITUTION OF WASHINGTON

SUPPLEMENTARY PUBLICATIONS
No. 5

The Magnetic Field of the Earth and Its Atmosphere

Time-Changes of the Earth's Magnetic Field
J. A. Fleming

Cosmic Disturbances of the Earth's Magnetic Field and their Influence upon Radio Communication - - - Arthur E. Kennelly

Tides in the Atmosphere - - J. Bartels

Being Three Lectures Delivered at the Administration Building of Carnegie Institution of Washington in March, 1932

UNIVERSITY OF MINNESOTA LIBRARY

Issued by
Division of Publications
CARNEGIE INSTITUTION OF WASHINGTON
Washington, D. C.
November 15, 1932

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero

Digitized by Google

Original from
UNIVERSITY OF MINNESOTA

UNIVERSITY OF
MINNESOTA
LIBRARY

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero

Digitized by Google

Original from
UNIVERSITY OF MINNESOTA

Reprinted from THE SCIENTIFIC MONTHLY, June, July, Aug., 1932. Vols. XXXIV and XXXV.

507
C21s

TIME-CHANGES OF THE EARTH'S MAGNETIC FIELD[1]

By J. A. FLEMING

ACTING DIRECTOR, DEPARTMENT OF TERRESTRIAL MAGNETISM, CARNEGIE INSTITUTION OF WASHINGTON

THERE is about the Earth a magnetic field. Its cause and origin are veiled in mystery as in the case of that other great natural phenomenon, gravitation. Unlike the latter, one can not immediately recognize the Earth's magnetism through any physical sense. An unexpected fall apprises one of the existence of gravitation, but no bodily effect is noticed in the Earth's magnetic field, although it is as real as that of gravity and is subject to relatively greater local anomalies than the gravimetric field.

The familiar compass-needle demonstrates that magnetic forces are present everywhere in the Earth. Ocular evidence of this force may also be obtained by its inductive magnetic action upon a material highly susceptible to such action, for example, an alloy with unusually great capacity for transient induced magnetization in weak magnetic fields such as that of our planet. Permalloy has been developed in recent years to supply the need of such a material to improve cable communication. When a thin long rod of permalloy is directed toward the north magnetic pole of the Earth's field, the magnetization induced in the bar because of that field is quite sufficient to lift small pieces of permalloy. But as the rod is turned with its length at right-angles to the field and thus in the direction least favorable to induction, it loses the magnetism induced by the Earth and will no longer support such metal strips, which fall.

[1] The first in a series of three lectures concerning the magnetic field of the Earth and its atmosphere, delivered at the Carnegie Institution of Washington, on March 8, 1932.

The picture of magnetic phenomena is incomplete if viewed only in a man-made laboratory, even though we can now produce there an artificial magnetic field within a space of a cubic inch which is about 100,000 times more intense than that of the Earth. Fortunately, Nature provides not only the Earth and its atmosphere as a great magnetic laboratory but also continuously performs experiments, utilizing as apparatus the Sun, the Moon and radiations from space. It is, however, only within historic times that we have appreciated the opportunity of putting this great laboratory to human use.

The discovery of the lodestone with its mystical power of attracting particles made of iron paved the way to the development of the magnetic compass, which has been in use by navigators since the twelfth century. This magnetic property of the lodestone—the "leading stone" of the Scandinavians, the "loving stone" of the French—was known to the Greeks according to authentic records some time about the end of the seventh century B. C. Various traditions ascribe such knowledge also to the Chinese as much as 2,600 years before the Christian era, and to the Japanese during the second half of the seventh century, but there is some question as to their authenticity.

In attempting to solve the mystery of the lodestone it was discovered that, when mounted in a block of wood and floated in water, one direction would always be indicated, that is, magnetic north and south. This was followed by

MAR 7 '33

559830

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero

Digitized by Google

Original from UNIVERSITY OF MINNESOTA

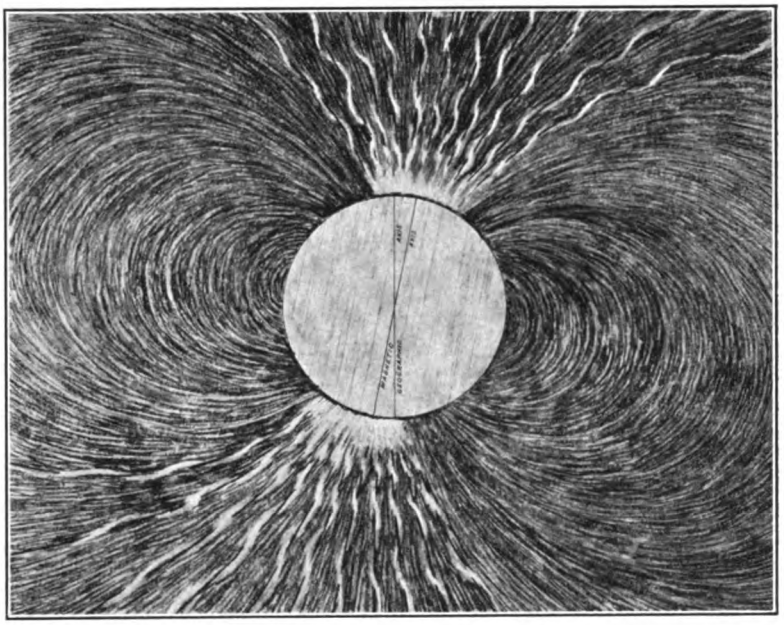


FIG. 1. THE MAGNETIC FIELD ABOUT THE EARTH

the first European treatise on the magnet written about 1269.

That property of the magnetic field of the Earth giving direction to the compass-needle was thus utilized some centuries before Columbus began his voyages to the western hemisphere. He, however, was the first to determine that the compass did not point true north except in certain places. We all know the story of the threatened mutiny on his first transatlantic voyage when the crew saw the compass pointed 10° west of true north instead of north as indicated by the pole-star, and how apparently he shifted the compass-card on its needle during the following night, thus quieting the fears of his men and inducing them to continue. But even to-day there are many who think of the compass-needle as showing direction "true to the pole of the heavens or the polar star."

Magnetic dip or inclination was unknown until 1576, when Robert Norman, a practical seaman and instrument-maker, published "A newe discovered secret and subtill propertie concernying the declinying of the Needle, touched therewith under the plaine of the Horizon." His discovery that the magnetic needle, when mounted on a horizontal axle so as to be free to move in the vertical plane, dipped below the horizon, gave the first hint that the source of the magnetic field of the Earth might be within the globe and not in the stars as previously supposed. It was not until 1600, however, that William Gilbert published his famous volume in which he pointed out that the Earth itself acts to a certain extent as though it were a great spherical magnet. Gilbert's conclusion thus preceded Newton's announcement of universal gravitation. Taken as a whole, the Earth is a feeble magnet. It is possible to magnetize our modern hard steel ten-thousand fold as much. Even so, since the globe is large, its total magnetism is equivalent in effect

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

to eight hundred quintillion one-pound magnets of our best magnet-steel, could they be placed at its center.

The Earth is not uniformly magnetized and the principal magnetic poles are distant 1,200 miles or more from its geographic poles. The north magnetic pole, first visited a century ago June, 1831, by Ross and again in 1903, by Amundsen, is on Boothia Peninsula in northern Canada. The south magnetic pole, in South Victoria Land, has not yet been visited. Thus the magnetic poles are not diametrically opposite each other, the line joining them passing some 750 miles away from the center of the Earth.

The magnetic field extends far out into space. Four thousand miles above the Earth's surface it is still one eighth as great as at the surface. One may picture it as made of innumerable lines of magnetic force or action closely packed as schematically shown in Fig. 1. These lines of force are parallel to the surface near the plane of the equator, but as they approach the magnetic poles they bend and converge. Minute electrified particles in varying numbers are coming continually from the Sun. Once within the Earth's magnetic field, these particles or corpuscles are entrapped by the outermost lines of magnetic force and travel in paths around them. They get deeper down in our atmosphere in the polar regions, where the magnetic-force lines are steepest. When the electrified particles pass through the atmosphere they cause the air to glow by their impact, causing the brilliant polar-light displays sometimes seen in the northern and southern sky. From simultaneous photographs of aurora, taken at two stations a known distance apart, it has been found that polar-light beams generally do not come closer to the Earth's surface than about 50 miles; some come no closer than 300 miles or more.

The Earth's outer crust or shell, some 50 or more miles thick, is not homogeneous and therefore is not uniform in its magnetic behavior. Thus there are many regions of local magnetic disturbance, such as are caused by magnetic ore-deposits, some so great as to give rise to local poles and other irregularities in the general magnetic field.

The study of the character and behavior of this field therefore calls for observations not only on the surface of our globe but also in its interior and in its atmosphere. This applies particularly to the higher atmospheric limits and to the Earth's enveloping skin

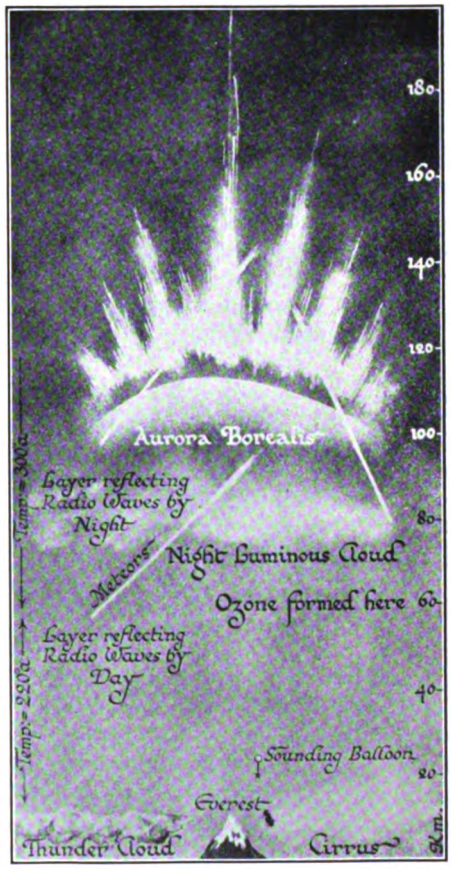


FIG. 1A. THE HEIGHTS OF VARIOUS PHENOMENA IN THE ATMOSPHERE
(AFTER DOBSON)

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

or crust, where we apparently must look for explanations of those constantly occurring regular and irregular variations with time of the magnetic field which are the subject of this paper.

That our magnetic field is subject to progressive change or secular variation, that is, a slow age-long variation, was first noted by Gellibrand in 1634. In a book published in London (June 12, 1634) entitled "A Discourse Mathematical on the Variation of the Magnetical Needle Together with its Admirable Diminution Lately Discovered" he announced for the first time that "Variation is accompanied with a variation." Besides the secular variation, other more or less regular time-changes include daily inequalities, taking place chiefly during daylight hours and varying in magnitude and character with geographic position, with the seasons of the year, and with disturbances on the Sun. There are also short-period, long-period and sudden-commencement disturbances, commonly designated magnetic storms, apparently accompanying solar disturbance and other cosmical phenomena.

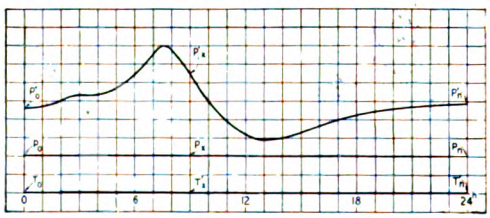


FIG. 2. GRAPH OF DATA VARYING WITH TIME

Much of what is known concerning time-changes can best be visualized graphically. Many of the photographic records upon which conclusions are based are in effect motion pictures of the experiments constantly being performed by Nature in her great laboratory. It is therefore desirable to give first some explanation of one method in common use to represent any quantity which varies with the passing of time or with some other variable. Consider, for example,

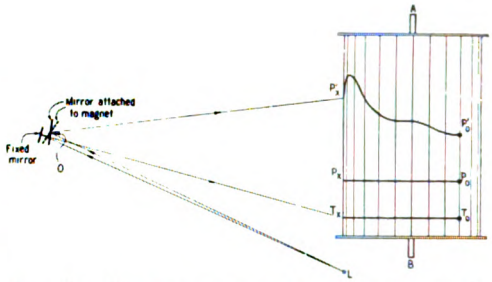


FIG. 3. SCHEMATIC DIAGRAM SHOWING PRINCIPLE OF RECORDING MAGNETIC VARIATIONS

any period over which a certain quantity is observed. It may be for centuries, for years, for months, for days, for minutes or for any other period represented by a straight reference-line as the one from T_o to T_n in Fig. 2. That line may be

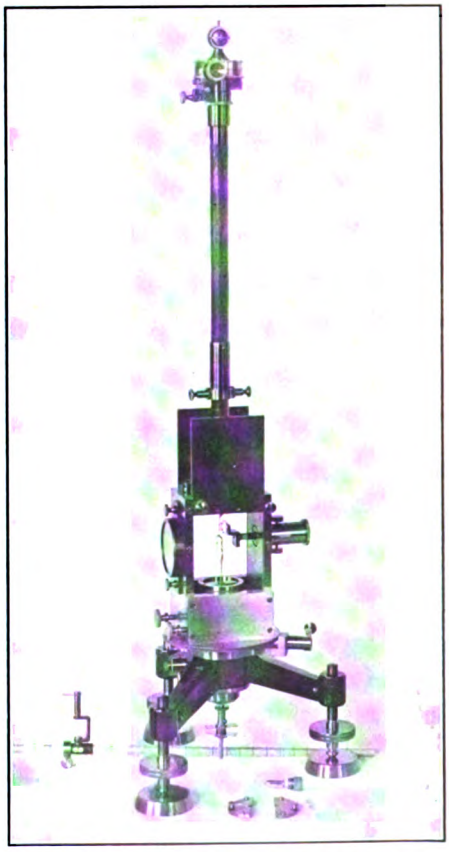


FIG. 4. MAGNETIC VARIOMETER

AS USED FOR RECORDING CHANGES IN COMPASS-DIRECTION

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

divided into a number of equal parts each corresponding to the selected time-unit, for example, in hours, in which case T_o represents 0^h or midnight of the day and T_n the following midnight. Each hour is then represented at successive points 1/24, 2/24, 3/24, . . . of the length T_oT_n measured from T_o. On the lines at right-angles to this line at any of these points then may be plotted to any arbitrarily chosen scale the difference between this reference-line and the observed value at any time T_x. The phenomenon being one in which there is no change during the time represented, the graph representing it would be a straight line such as P_oP_n parallel to T_oT_n. For some phenomenon not constant during the time-interval being considered the line joining values plotted to our arbitrary scale on perpendiculars at the successive unit time-points to represent the changing values will form some regular or irregular curve such as P_o' P_x' P_n'. In an instrument to record change in compass-direction, consider Fig. 3 as a horizontal projection of a mirror attached to a magnetic needle, the latter so suspended at a point above the paper as to be free to rotate about its vertical axis at O. Suppose a source of light at L providing a horizontal light-beam directed toward the mirror; when the compass-direction changes through a small angle, the mirror rotates with it to some position as that shown by the heavy dotted line, and the reflection of the light-beam changes from OP_o' to OP_x'. A second mirror, fixed in position, causes a steady reflection of the light-beam to give a reference-line corresponding to T_oT_n. Now if a sheet of photographic paper, suitably protected from all light except the reflected beam, be so mounted as to have uniform motion either in the vertical plane or on a cylinder rotating on an axle AB, then as the compass-direction changes, the light-beam focused on the sensitive paper gives a photographic record as the paper shifts.

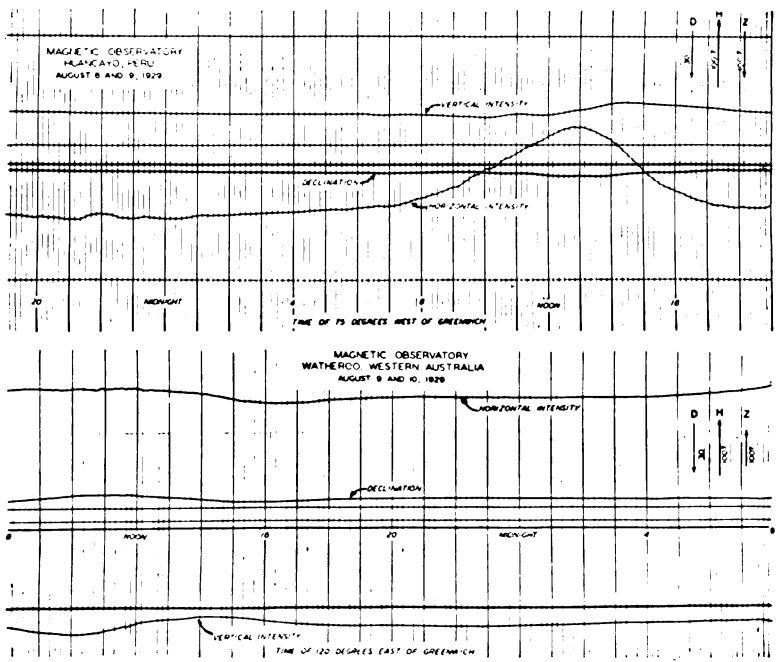


FIG. 5. MAGNETOGRAMS FOR TYPICALLY QUIET DAYS
RECORDED AT THE HUANCAYO AND WATHEROO MAGNETIC OBSERVATORIES, AUGUST, 1929

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

Upon developing this sensitized sheet we have a complete record of the movement of the compass-needle during the period. It is comparatively easy to determine by experiment or measurement of distances the length of the perpendicular to the reference-line of such a record for a unit angular motion as, for example, a single minute of arc or any other unit of measure. When such a method as outlined is translated into an actual instrument, as in Fig. 4, the optical and photographic recording devices intrinsically constitute substitutes for very long magnets which would be difficult to support so that they might swing freely with changes in the Earth's field. The length of the magnet in such a variometer is less than an inch, but with the optical arrangement this becomes theoretically infinitely long. Some actual photographic records of daily variations of the direction of the compass (magnetic declination) and of the forces acting in the vertical and horizontal planes are reproduced in Fig. 5.

Secular Variation

The usefulness for navigation at sea of magnetic direction or declination as indicated by the compass has stimulated and maintained interest in determining its value since the time of Columbus. Before the invention of chronometers it was thought that geographic position might be derived from knowledge of changes from place to place in magnetic declination and inclination. This led to the first systematic oceanic survey by the astronomer Edmund Halley in the Atlantic Ocean, during 1698–1700, on the

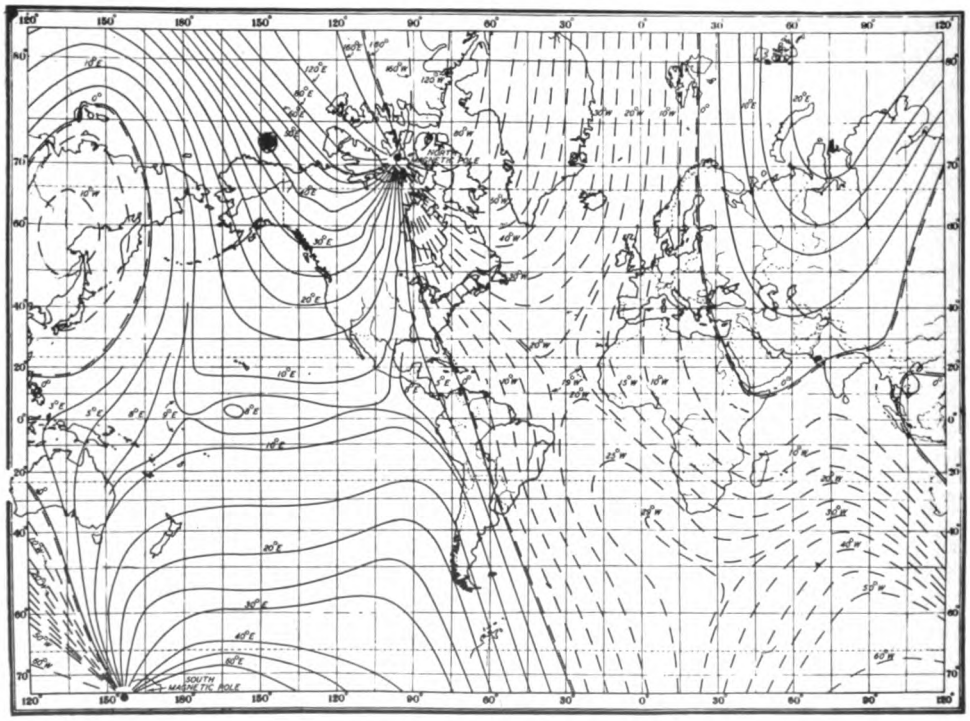


FIG. 6. CHART SHOWING LINES

ALONG WHICH MAGNETIC DIRECTION—DECLINATION—IS THE SAME FOR EPOCH 1930 BASED ON ISOGONIC CHART OF THE UNITED STATES HYDROGRAPHIC OFFICE

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

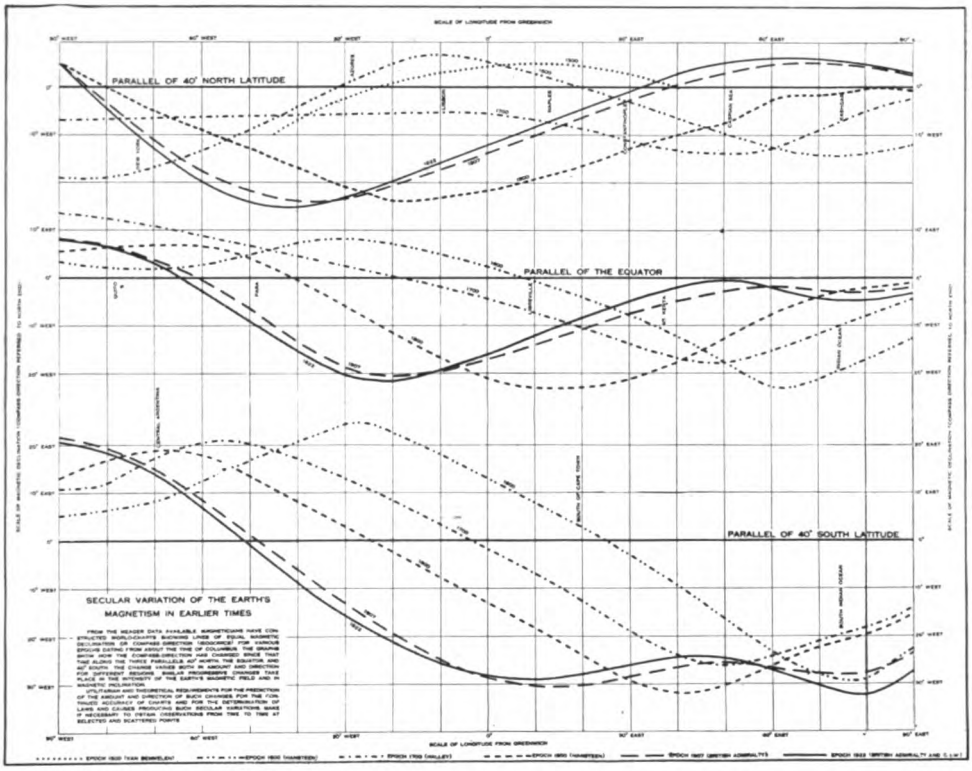

PARALLEL OF 40° NORTH LATITUDE
PARALLEL OF THE EQUATOR
PARALLEL OF 40° SOUTH LATITUDE
SECULAR VARIATION OF THE EARTH'S MAGNETISM IN EARLIER TIMES

FIG. 7. GRAPHS SHOWING SECULAR VARIATION IN DECLINATION OF THE EARTH'S MAGNETISM DURING 1500 TO 1922 FOR PARALLELS OF LATITUDE 40° NORTH, 0°, AND 40° SOUTH FOR LONGITUDES 90° WEST TO 90° EAST OF GREENWICH

sailing vessel *Paramour Pink*. As one result of his voyages the first isomagnetic chart was published. It showed lines at all points on which the compass-direction differed from true north by the same angle, that is, lines of equal magnetic declination or isogonics. This chart and succeeding ones based on later data from time to time show the progressive changes in the position of these lines—changes known as secular variation. Fig. 6, for declination, is based on the latest isomagnetic chart published by the United States Hydrographic Office and applies for the epoch 1930. Its contrast with Halley's chart strikingly indicates the great accumulation of observed values during the past three centuries—an accumulation to which the Carnegie Institution has made large contributions since 1905 through its mag-

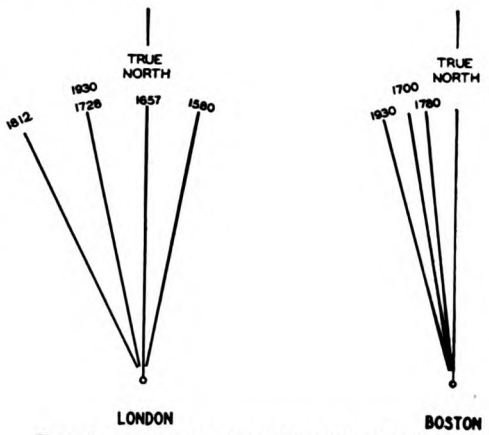


FIG. 8. SECULAR VARIATION OF COMPASS-DIRECTION AT LONDON AND AT BOSTON

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

netic-survey operations on sea and land. The secular changes in the compass-direction in earlier times are indicated by Fig. 7, along several different parallels of latitude for various epochs.

Another picture of secular variation utilizing observed compass-directions at London and at Boston is given by Fig. 8, showing the observed true bearing of the compass in different years. The importance of these changes in any practical use of the magnetic compass or needle may be realized by considering the observed data at London. There the magnetic needle pointed 11° east of north in 1580, changed gradually until it pointed 24° west of north in 1812, and since then has shifted eastward and now points only about 13° west of north. These results might be taken to indicate a complete cycle of change of about 500 years, but centuries more of observations are needed to verify such an indication.

For the purpose of illustration here, as well as later, let us conceive a thin, giant compass-needle about two miles long supported at its center by a pivot in which it is free to rotate, its north-seeking end taking at all times the direction of the Earth's magnetic field. The north end of this giant needle would move a little less than 100 feet for a change of one degree in direction or about one and one-half feet for a change of one minute of arc. At London its end would have moved westward from 1580 to 1812 more than 3,200 feet and then about 1,000 feet eastward to the present time. Here in Washington the annual change at present is such that the end of our giant needle would move because of it only about one-sixth of an inch per day toward the west, or a total of about five feet in the year. In the past 50 years this motion here would have totaled some 400 or 500 feet—a long city block—from the east.

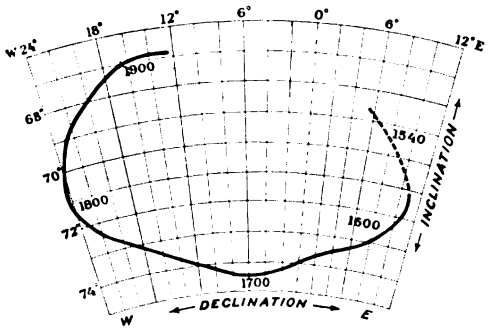


FIG. 9. SECULAR CHANGE IN MAGNETIC DECLINATION AND INCLINATION AT LONDON, 1540 TO 1900 (AFTER BAUER)

A more illuminating graphical method developed in an early paper by Bauer to represent observed data is illustrated in Fig. 9. In this the magnetic needle is considered as being supported at its center so as to be free to turn in any direction in space. The changing position of a needle so mounted would show by the motion of its end secular variations both in the horizontal and vertical planes. At London such a needle would have described a conical surface in a clockwise direction. However, similar graphs for other stations in various parts of the world show different periods and amplitudes of this motion in space. So we may not assume a cyclic secular-variation of common period applying to the whole Earth. We must, therefore, dismiss as insufficient the popular notion that changes in compass-direction arise wholly or mainly from a shift in the position of the magnetic axis or of the magnetic poles of the Earth.

There is another interesting possible method by which secular-variation information may be extended to times more remote than those for which observations exist. When lava cools and freezes following a volcanic outburst, it takes up a permanent magnetization dependent upon the orientation of the Earth's magnetic field at the time. This, because of small capacity for magnetization in the Earth's weak field after freezing, may remain practically constant. If this assumption be correct, the direction of the

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

originally acquired permanent magnetization can be determined by laboratory tests providing every detail of orientation of the mass tested is carefully noted and marked when it is removed. Samples of lava-flows of known date from Mount Etna back to 1284 have yielded fairly consistent data for magnetic declination and inclination, which apparently indicate a secular-variation period of about 750 years. Similar measurements have been made using lava-flows caused by eruptions in the fourth century B. C.; however, results depending upon measurements of this kind must be used with caution. There is another possible source of such data, although certainly even more speculative than the lava-flows. When vessels made of clay containing iron compounds are fired, they take on and retain a permanent magnetic condition and axis-direction depending upon their orientation in the Earth's field at the time of firing. These are negligibly influenced by later changes in the Earth's field. Determination of direction of the magnetic axis may then give some idea of the inclination of the Earth's magnetic field at the time the vessel was made.

During the past quarter century marked progress has been made in accumulating accurate and coordinated information which is beginning to shed light on the character of the changes in the magnetic elements particularly in those regions controlled by the more advanced nations. Any attempt, however, to arrive at a solution by examining what takes place within a limited area or during too short an interval of time is not only a hopelessly inadequate undertaking but is very likely to lead to erroneous suppositions. It is but another instance of the danger of drawing conclusions from half-truths so aptly illustrated by the often-quoted dispute of the

> . . . six wise men of Industan to learning much inclined
> Who went to *see* the elephant though all of them were blind.

Like the subject of that classical investigation, this is also of mammoth proportions, and like those seekers for truth, investigators of magnetic changes have given clear and valuable reports of what has come within their observation, each of which is essential to the construction of the complete picture. But as vision improves with the gradual accumulation of details, the complex character of the subjects begins to become apparent, and some real progress toward a reconciliation of the differences in first impressions may now be expected.

As stated, the scattered observations of declination run back over 300 years in a few limited localities. The collection of observations of inclination, due of course to its smaller practical utility as well as to the greater difficulty attending its measurement, is much less abundant. It is now almost exactly 100 years since Gauss first described a method of obtaining the absolute measure of the magnetic intensity, or the strength of the magnetic field. It is really only since that time that serious research in secular variation —one of the most fascinating and at the same time the most suggestive of the time-change problems of the Earth's magnetism—has been possible. One hundred years would be scant time for the changes of the slow-moving forces to produce effects sufficient for the purpose, even if a complete record of the changes for that period were at hand. But the record is fragmentary at best, so that what is known of secular variation prior to renewed activity in the study of the subject manifested by the establishment of a considerable number of permanent and well-equipped observatories during the closing years of the past and the opening years of the present century is in general limited to a few restricted regions or to scattered localities.

Whatever may be found to be the

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

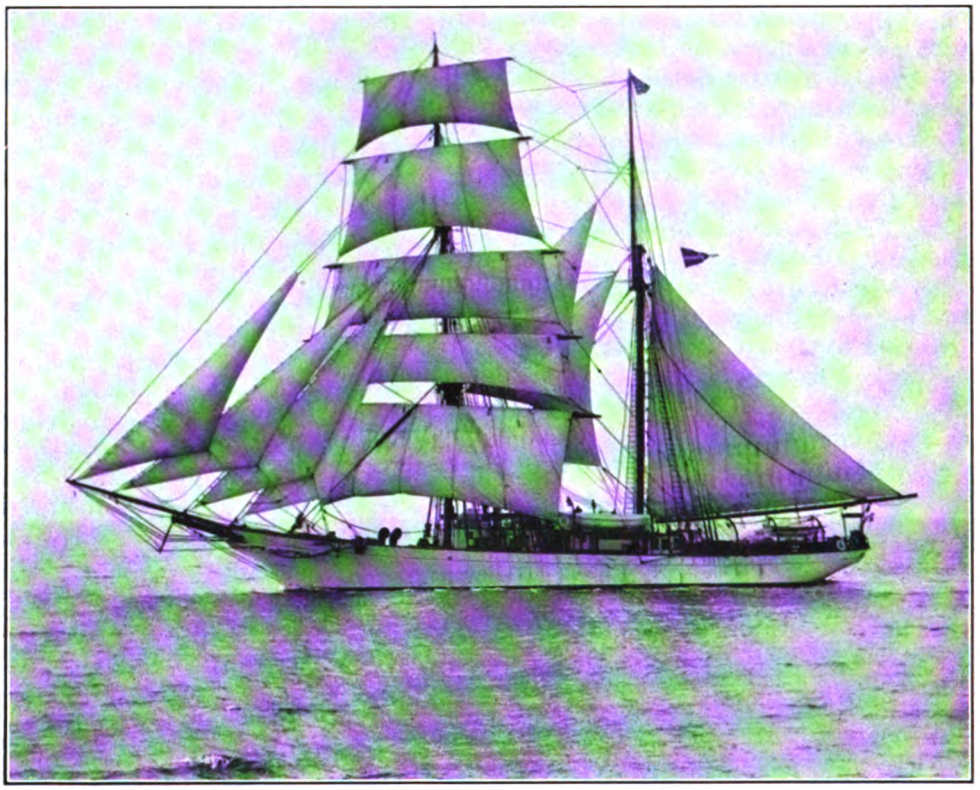


FIG. 10. NON-MAGNETIC VESSEL *CARNEGIE*, ELBE RIVER, JUNE, 1928

source of that magnetization, any changes affecting it must take into consideration the nature of simultaneous changes appearing over the entire surface of the planet. There is no known means of "remote control," no method by which in a carefully equipped observatory or comfortable laboratory in an agreeable climate surrounded by the comforts of home, a competent staff of investigators can apply themselves to the solution of this problem. Only a portion of the land surface of the Earth is peopled by nations whose intellectual and material equipment enables them to maintain magnetic surveys, and of the entire surface of the Earth but a minor fraction is of land. There are the backward lands, the jungles, and the deserts; there are the remote and all but inaccessible islands of the great oceans, and great expanses of the sea where no land is; there is the far frigid north and the frozen unknown of the farther south; such places must be included in a complete and homogeneous network of stations if a satisfactory picture of what is taking place is to be drawn. Such places can not contribute the information of themselves; expeditions must be organized by others who are able to go and seek it—not once, but repeatedly—since it is not a condition, but the changeableness of a condition which is sought. The phenomenon is not static but dynamic; it is not a still picture which we visualize once for all but a moving picture requiring repeated exposures, and each exposure meaning a long and arduous journey to parts where means of travel

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

are primitive or entirely lacking, where oftentimes expensive expeditions must be organized and financed to secure pictures in the setting desired.

Often when a place has been revisited after the interval of years it is impossible to find and make a redetermination at the same position as that previously used, and a new point must be chosen. But as the time-changes sought are relatively very small, and as local displacements often cause considerable differences due solely to peculiarities of the local geology, a new uncertainty is introduced to increase the difficulty of the task. Obviously the undertaking is too great for solution without the cooperation of scientific agencies of all countries. It is a satisfaction to record that there is a continually increasing number who are finding fruitful ways of contributing the details necessary to complete the picture.

As will be realized, the fascination—we may almost say romance—of the study of these data extends further to the efforts in their accumulation. Observational stations for the study of variations and perturbations must be located in out-of-the-way places even in populous countries to avoid those artificial disturbances arising from widespread use of electrical currents and devices. There is a lack of comfortable traveling conveniences in unexplored regions, despite the automobile, the airplane and the dirigible, though these are all combining to lessen the old difficulties and the time required in getting about.

In this magnetic survey to determine magnetic distribution and secular variation of the Earth's field the Department of Terrestrial Magnetism of the Carnegie Institution of Washington has done much. This extended on land to those countries and regions where there were or are no established magnetic-survey organizations, or where existing agencies for one reason or another welcomed cooperation. Thus, since 1905, almost 200 magnetic exploring expeditions to remote and little-explored regions were made. During 1905–29, also, an intensive magnetic survey of all oceanic areas was executed, for the first four years with the chartered brigantine *Galilee,* and during 1909–29 with the specially constructed, non-magnetic vessel *Carnegie* (Fig. 10). The latter vessel was unfortunately destroyed by a gasoline explosion and fire in Apia Harbor, November 29, 1929, during her last and seventh

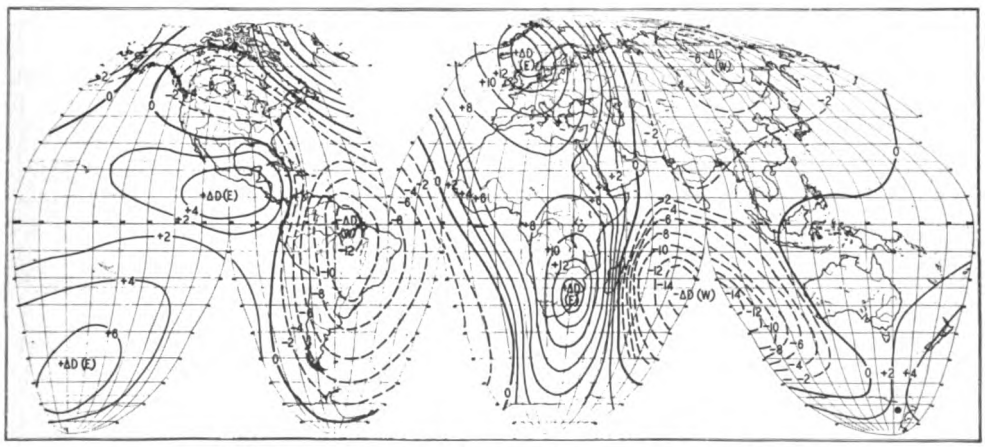


FIG. 11. ISOPORIC CHART FOR DECLINATION

THAT IS, CHART SHOWING LINES OF EQUAL ANNUAL CHANGE, APPROXIMATE EPOCH 1920–25

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

world-wide cruise. The number of magnetic distribution-stations of the Institution on land and sea now totals nearly ten thousand. During the past decade ten per cent. of these have been reoccupied for secular-variation data.

The secular-variation data being assembled, isomagnetic charts (Fig. 6) may be prepared for various epochs upon which to base theoretical discussions. In succeeding epochs because of secular variation, shifts of the isomagnetic lines have occurred. It is then possible to join by a new set of lines those points past which the isomagnetics—as those of compass-direction or declination—have made the same progress. Thus, for instance, those places at which the declination has changed at the rate of one minute of arc a year, let us say to the eastward, are joined together. The same is done for changes of two minutes, three minutes, and so on up to the maximum rate of change of about one quarter degree, neglecting the immediate vicinity of the magnetic poles. Lines so drawn are called isopors or lines of equal marching. Only recently has it been possible to attempt drawing such isopors for the whole world with any degree of detail (see for example, the isopors of declination in Fig. 11). The picture resulting from these preliminary charts has presented the whole question of secular variation in a new light and has raised questions of broadest geophysical significance.

While it may be true that the rotation of the Earth with its magnetic field reaching out from it and surrounding it like a mantle constantly acted upon by radiations from the Sun and from the depth of space, subjects that field to a progressive precessional effect, what has long been suspected is becoming more and more apparent. A large part of the changes in the characteristics of the magnetic field has its origin not from influences impressed upon it from without, but arises from silent but titanic forces ceaselessly at work deep within the Earth itself. It must have been something of this sort which was in the mind of the Norwegian magnetician of the past century when he said that "the variations of the magnetic needle are a mute language revealing to us the changes perpetually going on in the interior of the Earth." And when we see the rise and fall of the rate of the secular change, the slow expansion and then the gradual retraction of the areas within which there have been excessive alterations in any of the magnetic elements, we realize there are still active changes going on in the Earth's interior.

On the isoporic chart for declination (Fig. 11) drawn for the approximate epoch 1920–25, a line showing no change over the period of a year runs from Nova Zembla off the northern coast of Russia, southward passing east of the Caspian Sea, thence continuing across Arabia and the island of Madagascar. East of this line the north end of the needle is pointing yearly farther west at a rate which increases slowly as the distance from the zero-line is increased, reaching a moderate maximum somewhere in eastern Siberia or Mongolia. The changes in the Indian Ocean are supposed to be larger than in Asia; this region is one where there are but scanty data available. However, to the west of that line of no annual change, over the greater part of Europe and extending somewhat into the Atlantic, there is a region of which we can speak with assurance, and one which presents a very interesting phenomenon. Numerous observatories have kept a continuous record of magnetic changes for nearly 30 years, some much longer, so that for that length of time the picture is for the most part complete. Proceeding westward from the Siberian border, we find the declination-isopors representing an-

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

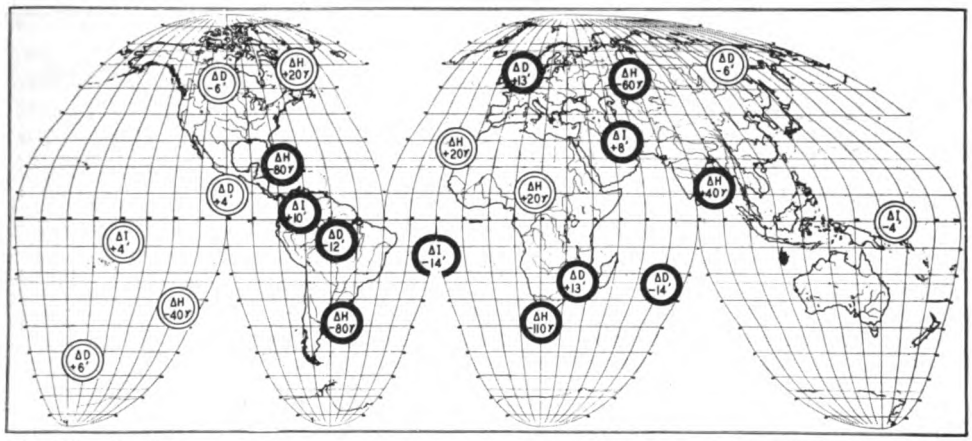


FIG. 12. DISTRIBUTION OF FOCI OF RAPID ANNUAL CHANGE OF THE MAGNETIC DECLINATION, INCLINATION AND HORIZONTAL INTENSITY, APPROXIMATE EPOCH, 1920–25

nual changes of one minute, two minutes, three minutes, and so on, packed quite closely together so that when we have reached Great Britain and the North Sea the annual rate of change in 1925 was nearly 13 minutes. The area having this large change is relatively small, so that the isopor takes the form of a small closed oval, surrounded by larger ovals successively representing the smaller changes. Along the northern part of Africa the changes are less rapid but in South Africa there is another focus of rapid change represented by concentric ovals on our isoporic chart. Unfortunately, there are no observatories at the present time in all of Africa south of Helwan near Cairo, so all we know of conditions there has been gleaned from occasional field observations.

But the foci of isopors are not permanent. The center of rapid change in western Europe has developed since the year 1900. If isopors are drawn for one-minute intervals, more than a dozen will be crossed at the present time in going from Ireland to the Ural mountains, whereas in 1905 scarcely more than one or two would have been crossed in the same distance. Now (in 1932) the zero-isopor is as described at about 60° east longitude; in 1905 it was in central Siberia at about 90°. So that while these ovals of our picture are moving outward from a center somewhere north of Scotland much as waves move in a pond from the spot where a stone has fallen into the water, the zero-line as a sort of shore-line against which these waves are beating has moved west to meet them. What the ultimate development of these figures will be we can only surmise, but there is reason to suppose that the dilation of these figures will be followed by a subsequent contraction. In eastern South America across a zero-isopor which passes from Labrador down the Atlantic past Cape Verde and St. Helena, there is a focus of opposite sign to those in Europe and South Africa, and the lines about this focus we know are moving inward. Do the lines move alternately inward and then outward, or do they continue to move inward until the focus disappears, perhaps to reappear elsewhere? We can not answer these questions until time has supplied the necessary knowledge, or until some geographical explanation has been found which will enable us to make a safe prediction.

The foci of isopors characteristic of the charts showing equal annual changes

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

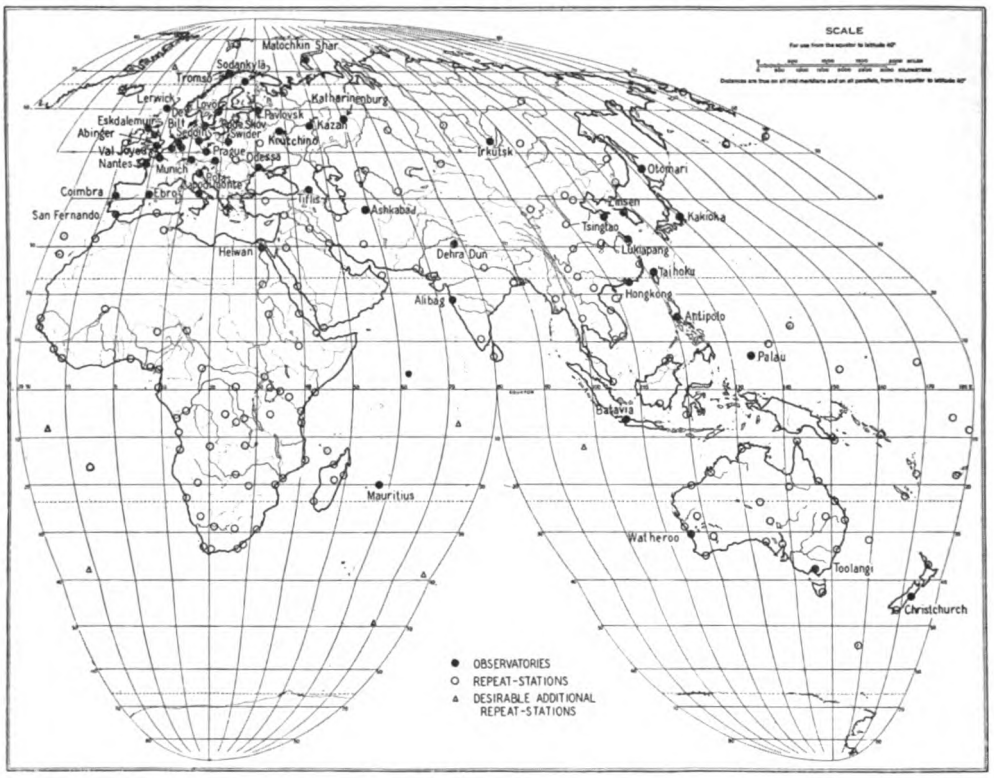


FIG. 13. DISTRIBUTION OF MAGNETIC OBSERVATORIES, REPEAT-STATIONS, AND DESIRABLE REPEAT-STATIONS IN EUROPE, AFRICA, AUSTRALIA AND INDIAN OCEAN

in declination are present also on the corresponding charts for the other elements. The distribution of these foci is noteworthy (Fig. 12). They are practically all found in the hemisphere containing the great land-masses with the intervening Atlantic Ocean. Such foci as are found in the Pacific hemisphere are of but moderate intensity and not well defined. This fact is doubtless significant, though what the significance may be we can only conjecture. This relation of large and rapidly changing rates of change of the intensity and direction of the magnetic field to the surface structure of the Earth can scarcely be accidental; it is natural to suspect that there is a causal relationship existing between crustal or subcrustal movements and these magnetic manifestations. Perhaps there are changing mechanical stresses, or possibly a changing distribution of internal heat, which in turn affects the direction or magnitude of subterranean electric currents. The phenomenon certainly emphasizes the warning of Maxwell that we must not suppose the inner history of our planet has ended.

The following conclusions have been drawn from the extended mathematical analyses in the Carnegie Institution's Department of Terrestrial Magnetism of data for mean epochs 1842, 1882, and 1922. The main cause of the secular variation arises from a system of forces embedded in the Earth. Secular variation is caused not only by a change in direction of magnetization but likewise by a change in the intensity of

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

magnetization. The average annual decreases in magnetic force have been larger for the southern, or water, hemisphere than for the northern, or land, hemisphere, while the average equivalent intensity of magnetization over land areas is somewhat larger than that over oceanic areas. There appears to be a small decrease each year in magnetization—approximately one fifteen-hundredth part. The Earth's total magnetic field at any one time is apparently attributable to the extent of about 94 per cent. to an internal magnetic system and to an extent of about 6 per cent. to external systems.

Diurnal-variation

The next important time-change—the solar diurnal-variation—in the Earth's magnetic field was discovered in 1722, at London, by a mechanician and clock-maker named Graham. It is stated that at Louveau, Siam, in 1682, experiments in the presence of the King showed the compass-direction different on seven different days; probably these were made at different times of the day and thus were really the first observed indications of diurnal variation.

The length of time required for collecting the necessary data for the study of the diurnal variation repeated day by day, is more commensurable to man's lifetime and that problem can, therefore, be studied at magnetic observatories within a reasonable time with much more detail than can the slow secular variation. Magnetic research has already yielded correspondingly more definite results in this aspect of the subject and has shown promising lines for future work. And while on one side the search

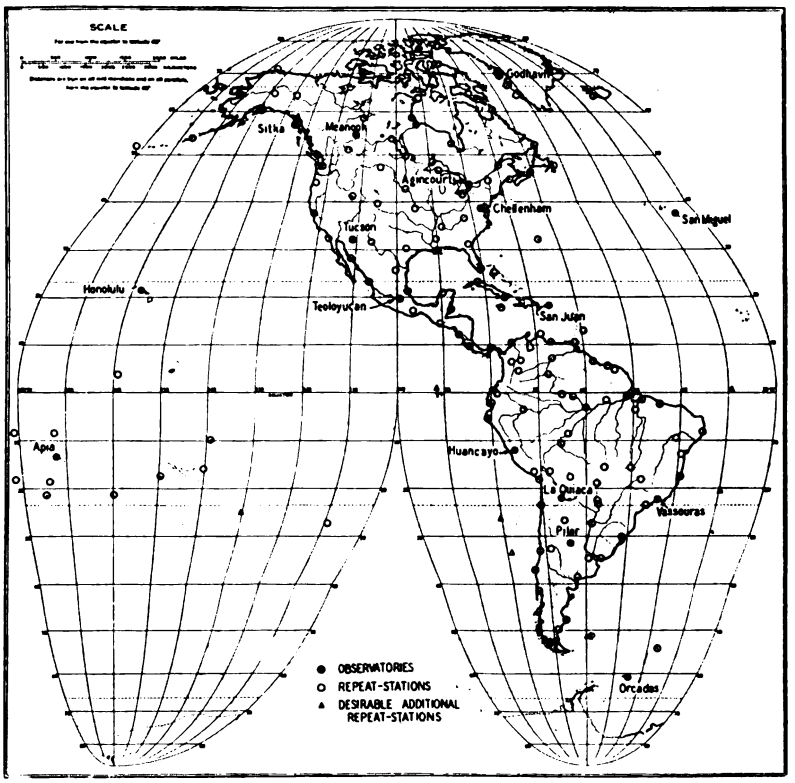


Fig. 14. Distribution of magnetic observatories, repeat-stations, and desirable repeat-stations in North America, South America and Pacific Ocean

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

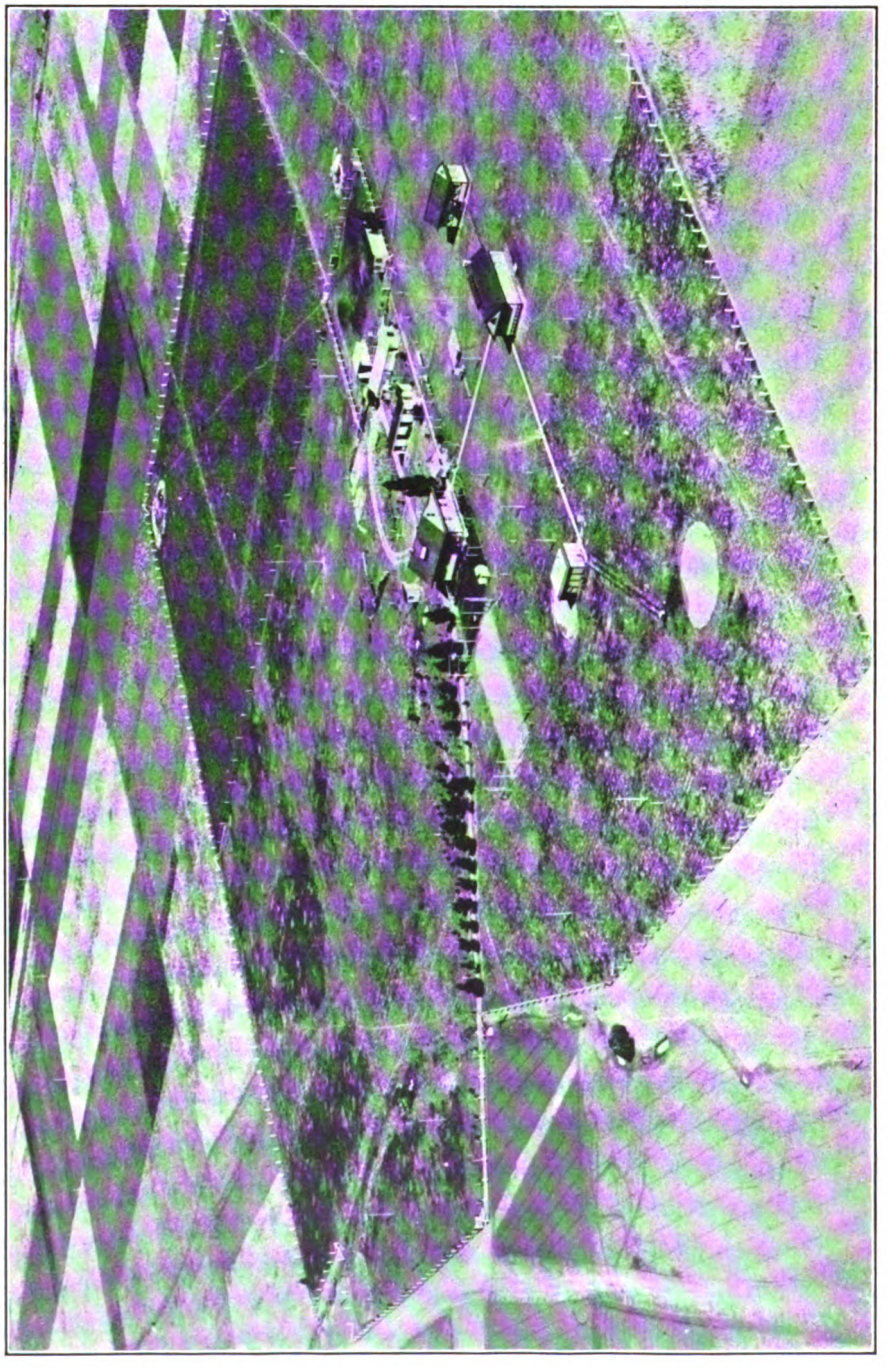


FIG. 14A. SITE AND BUILDINGS OF HUANCAYO MAGNETIC OBSERVATORY FROM THE AIR, APRIL, 1931
—*Courtesy of Johnson-Shippee Expedition*

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

for the explanation of the main part of the Earth's magnetic field and its secular variation is hampered by the fact that we know only one planet, namely, our own, and that we have to put up with those irregularities in its crust, that distribution of land and sea which we find upon it, we can on the other side collect data for the diurnal variation for very many days and utilize the natural differences in season, in magnetic disturbance, in sunspot-numbers for testing theories and drawing conclusions.

The world-distribution of existing magnetic observatories is shown by the black dots on Figs. 13 and 14; the open circles and the small triangles on these charts indicate desirable repeat field-stations for the determination of secular variation. From the first chart, showing Europe, Asia, Australia, Africa, and the Indian Ocean, we see how great a majority of the observatories is in Europe. It is especially noteworthy that on the whole of Africa there is only one existing magnetic observatory and that in the extreme northeastern part. When it is recalled that several foci of large secular change are located in Africa, the importance of additional magnetic observatories there is apparent. The second chart shows the distribution of existing observatories in North and South America and in the Pacific Ocean. Such observatories and laboratories have, indeed, been established by forward-looking and scientific-minded nations, and they are an indispensable source of data which the solutions of magnetic questions require. Our own country, through the work of its Coast and Geodetic Survey, has contributed much, especially in the past thirty years through its magnetic surveys of the United States, its territories, and coastal waters, and through the maintenance of five well-distributed observatories. The Institution also established and maintains two magnetic observatories, the one near Watheroo, Western Australia, and the other near Huancayo, Peru (Fig. 14A). The latter is uniquely located on the magnetic equator at an elevation above sea of 11,000 feet, while the former adds a much-needed station in the southern hemisphere.

The diurnal inequality varies with the season of the year, the range of this inequality being greater in summer than in winter. As one goes from temperate zones to the frigid or to the torrid zones, these summer and winter inequalities present widely differing features. The extent to which such an inequality varies throughout the year is readily seen by the graphs in Fig. 15. It will be immediately apparent that diurnal variation in its main features progresses according to local mean time. Thus this variation is connected with the Earth's rotation and, as its major tendency follows the apparent motion of the Sun, it may be presumed that the Sun is an important factor in this daily phenomenon. This variation also is the first indication that the Earth's magnetism responds to outside influences which find their origin in solar activity and act upon the upper regions of the atmosphere. Fig. 16 also indicates how this diurnal variation changes with season, the greatest ranges always occurring in the summer months.

Here in Washington the north end of the compass-needle on a magnetically-quiet day starts swinging eastward, beginning with sunrise, continuing so until some time between 8 and 9 o'clock, when it swings rapidly towards the west until between 1 and 2 o'clock and then returns to its first position. The end of our giant two-mile needle would have an extreme motion in the course of daylight of about 10 to 15 feet; during the night hours its motion would be much slower and much smaller.

The diurnal variation of declination at Watheroo for the year 1930 by seasons yields three curves (Fig. 17) exhibiting

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

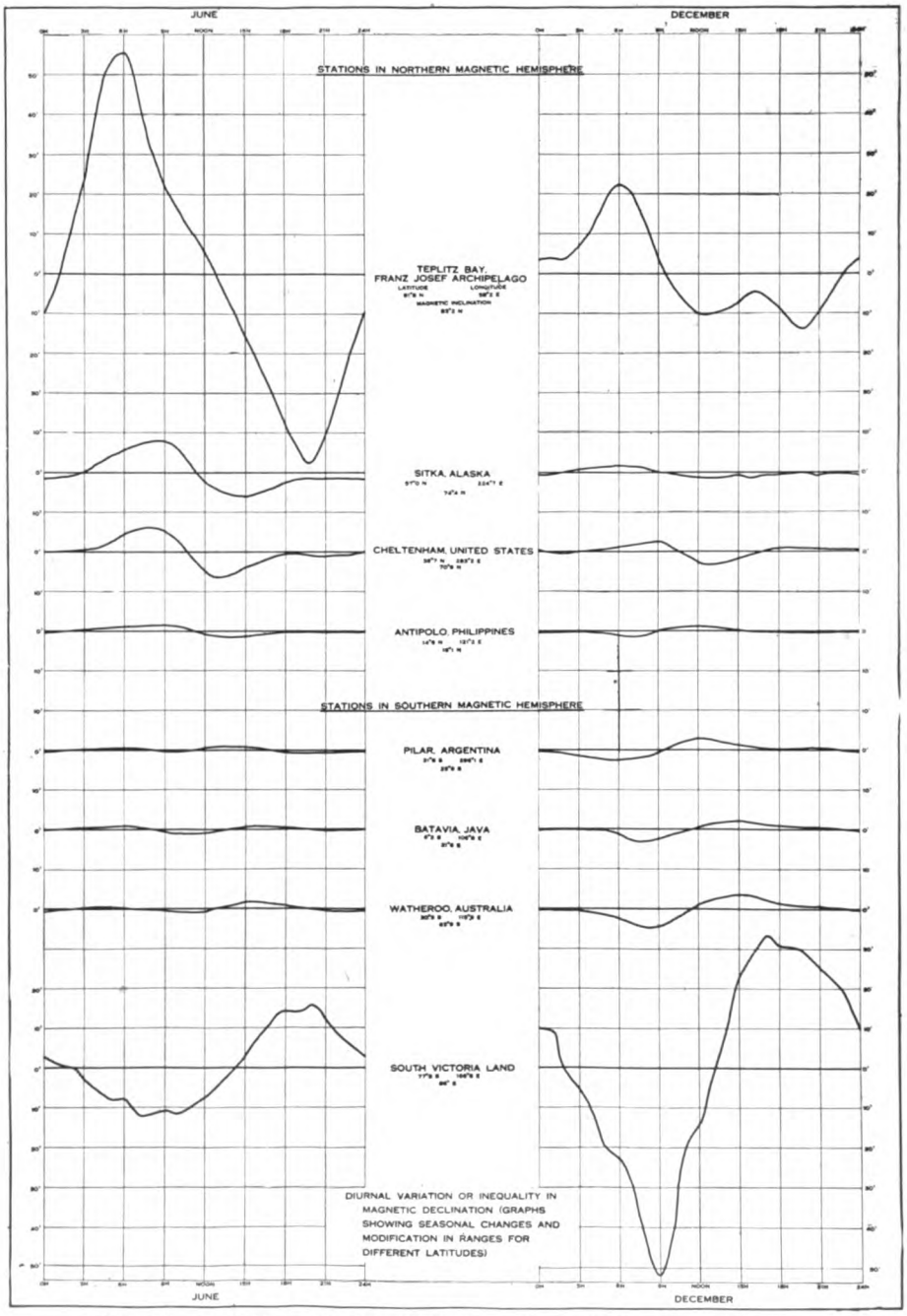


FIG. 15. DIURNAL VARIATION IN MAGNETIC DECLINATION

SHOWING CHANGES FOR DIFFERENT SEASONS IN DIFFERENT LATITUDES—UPWARD MOTION OF THE CURVES INDICATES INCREASING EAST DECLINATION OF THE NORTH-SEEKING END OF THE NEEDLE

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

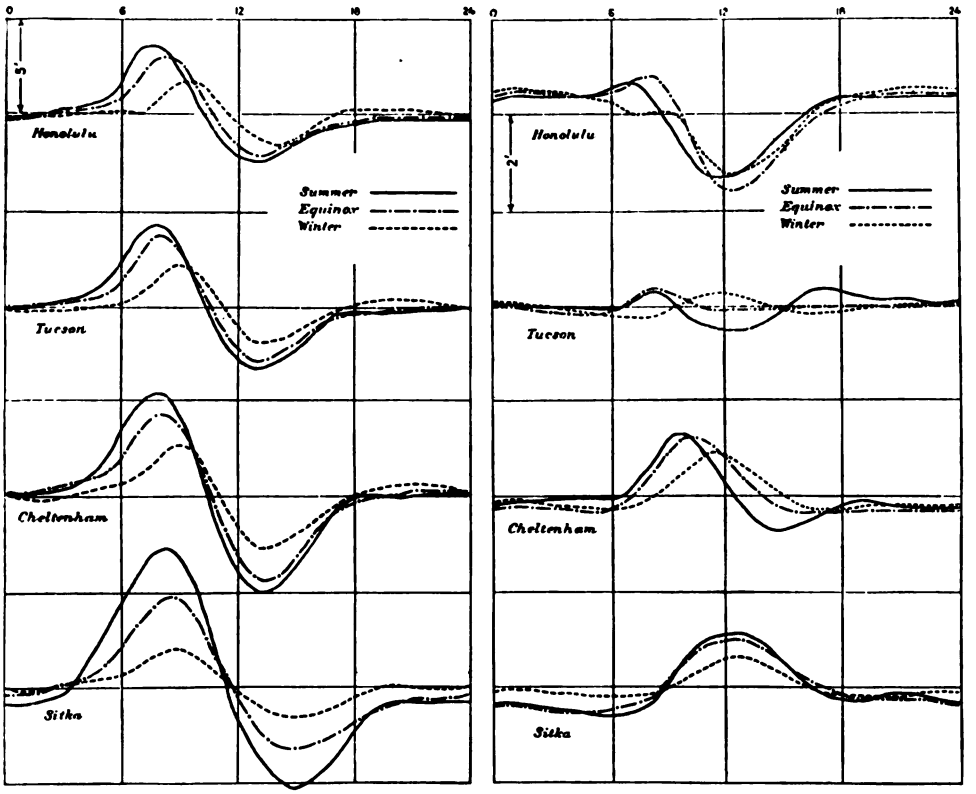


FIG. 16. DIURNAL VARIATION OF MAGNETIC DECLINATION (LEFT) AND INCLINATION AT HONOLULU, TUCSON, CHELTENHAM AND SITKA OBSERVATORIES FOR SUMMER, EQUINOX AND WINTER (AFTER U. S. COAST AND GEODETIC SURVEY)

the "southern" type of variation which characterizes a magnetic observatory situated at about 30° south, where the focus of the external electrical current-system causing diurnal variation passes approximately overhead daily. The variation is greatest at the December solstice and least at the June solstice due to the fact that the ionization produced by the Sun is greatest or least respectively over the southern hemisphere at those seasons. At Huancayo, on the magnetic equator, the corresponding graphs (Fig. 18) show the variation at the December solstice, when the Sun is actually south of Huancayo, is of the south temperate type, while when the Sun is over the northern hemisphere the variation is of the north equatorial type. This is an excellent indication of the changes which take place in the overhead current-system from season to season. Instead of moving northward or southward with the seasons as one might expect, this series of curves indicates that the southern current-circuit or the northern current-circuit expands according as the Sun is over the southern or northern hemisphere, so that during the northern summer Huancayo is included in the edge of the northern circuit while during the southern summer it falls well within the southern circuit. Similar phenomena are exhibited by the diurnal variations at Batavia and Apia, other observatories near the magnetic equator.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

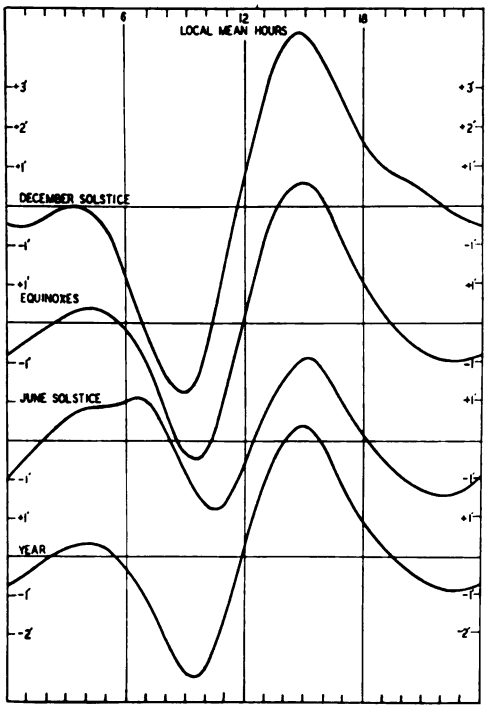


FIG. 17. MEAN SEASONAL AND ANNUAL DIURNAL-VARIATION IN MAGNETIC DECLINATION AT WATHEROO MAGNETIC OBSERVATORY, 1930

SMALLER PERIODIC VARIATIONS—LUNAR-DAY AND ANNUAL

Besides the ordinary diurnal variation there is another, small and quite systematic, namely, that associated with the Moon's position.

We have seen in several figures the average daily influence of the Sun on the magnetic force as revealed by the 24 average hourly mean values for a number of days giving the systematic changes in the course of a solar day, from midnight to midnight, that is, from one lower transit of the Sun to the next. In the same way, we can speak of a lunar day, reckoned from one lower transit of a moon to the next. This interval is, on the average, 50 minutes longer than a solar day; for convenience, we divide it into 24 lunar hours of equal length. By combining the magnetic values for each corresponding lunar hour of a large number of days, we obtain the influence of the Moon on the Earth's magnetic field, that is, the lunar diurnal-variation. The magnitude of the lunar variations is less than one tenth of the solar and can be derived only by careful analysis from very many observations.

While the lunar variation is too small to have practical interest for navigational purposes, it is very important for the investigation of the highest layers of the atmosphere, where these magnetic variations are produced. The simple nature of the lunar variations, the double wave, indicates their tidal origin, that is, their relation to the same forces which cause the familiar regular rise and fall of the water in the ocean and which produce similar and even more regular movements in the atmosphere.

The full significance of the lunar variation is brought out if we calculate it separately for the different phases of the Moon, which are shown in Fig. 19, for

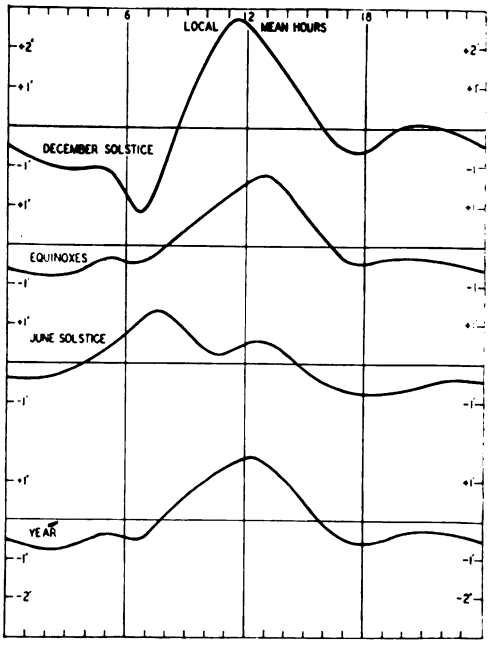


FIG. 18. MEAN SEASONAL AND ANNUAL DIURNAL-VARIATION IN MAGNETIC DECLINATION AT HUANCAYO MAGNETIC OBSERVATORY, 1930

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

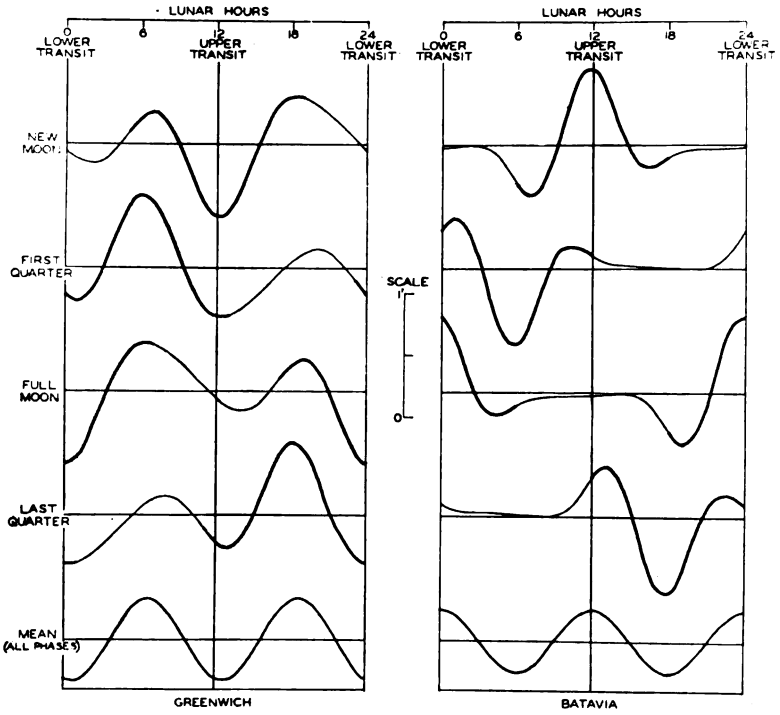


FIG. 19. LUNAR DIURNAL-VARIATION EAST MAGNETIC DECLINATION IN SUMMER

data from Batavia and Greenwich. These curves are based on 63 years of observations, or over 180,000 hourly observations in the four summer months May to August. The greater variation is in daylight hours, this effect of the tidal movements being enhanced by higher ionization, higher conductivity of the atmosphere. From our knowledge of the tidal movements and of the lunar magnetic variations, we can infer the change of ionization in the course of the solar day, and also the different physical state of the atmosphere in the different seasons, in different stages of the sun-spot-cycle, and at different degrees of magnetic disturbance. Note that the Batavia and Greenwich curves have opposite phase—Batavia a maximum at transit, Greenwich a minimum—because they are situated on opposite sides of electric current-system in the upper atmosphere which produces them.

It is very likely that lunar variations originate in even higher layers of the atmosphere than the solar variations, because they are so extremely sensitive to changes in magnetic activity as shown in Fig. 20. In Batavia the lunar variation is just as regular on disturbed days as on quiet days, but the range is tenfold as great. The location of an observatory is an important consideration affecting the evidence it provides for the study of this phenomenon. The Institution's observatories at Watheroo and Huancayo are key stations in an investigation on lunar diurnal-variations, the former being in the center of the current-system producing it and the latter on the magnetic equator.

When monthly values of compass-direction are corrected for the progressive secular change, they show a small variation with the year as a period. This, known as the annual variation, is a cyclical change and should not be confused with the annual change which

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

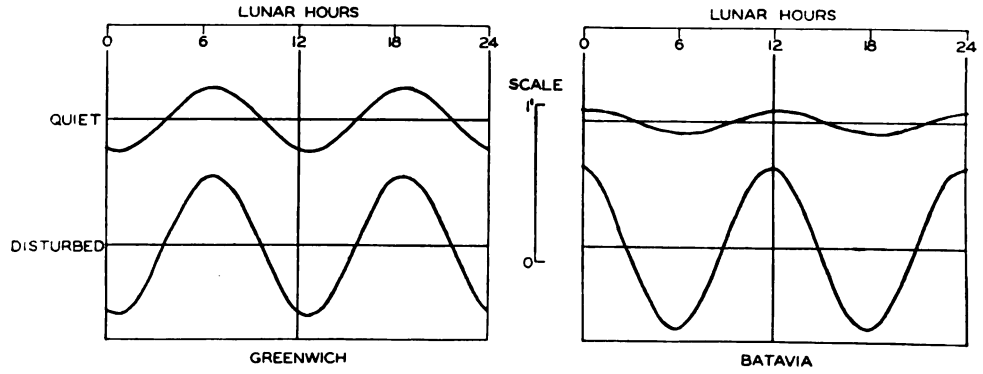


FIG. 20. LUNAR DIURNAL-VARIATION EAST MAGNETIC DECLINATION ON MAGNETICALLY QUIET AND DISTURBED DAYS

means the change in one year due to secular variation. This annual variation is a minute quantity and for stations in North America shows a total range of about one minute of arc. Thus the ends of our giant compass-needle at Washington would oscillate because of this variation during the present year through little more than one foot. So far as investigated, the cause of this variation appears to be outside the Earth.

A study of the time-changes affecting the magnitude and direction of the forces controlling the movement of the compass-needle has shown us that both the Sun and the Moon exert a subtle influence over them, and it is but natural to infer that a similar influence emanates from the planets or from the distant stars. Such a possibility has not been overlooked but so far there is no positive evidence from available data that anything of that kind exists.

REGULAR AND IRREGULAR VARIATIONS AND MAGNETIC ACTIVITY

There are other time-changes of quasi-regular and of irregular types. These are associated with what we call the Earth's magnetic activity or, let us say, its general state of magnetic rest or magnetic unrest.

This magnetic activity at a given station, during any interval, may be defined as a measure for the frequency and intensity of marked irregular deviations—magnetic storms—for example, from the normal diurnal variation, in that interval. There are many ways in which such a definition may be numerically expressed. The simplest and now most generally used is the international characterization. In this every observatory, from inspection of the character of its photographic records, assigns to each 24 hours between successive Greenwich midnights a "character-figure" on a scale 0–1–2. The character "0" applies to quiet, "1" to moderately disturbed, and "2" to greatly disturbed days. The adopted daily values are the averages for all collaborating observatories, the number of which increased from 30, when this measure was begun in 1906, to about 45 in 1932.

A more detailed method of measuring activity is that called the u-measure. This depends upon the interdiurnal variability, that is, the average difference regardless of sign, in the force directing the compass between successive daily means.

During days of character 2 our giant two-mile needle will have violent oscillations causing its north end to move

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

through as much as 100 feet here in Washington. At stations in polar regions, these disturbances are more violent because of the proximity of the magnetic poles. Actual records for Arctic stations have been obtained at times which would indicate that the north end of our giant needle would have shifted during such disturbance 20° to 30°—equivalent to a total displacement of its end through distances of about 2,000 to 3,000 feet. When it is borne in mind that such deflections may occur in a few minutes of time, the agitation of the Earth's field during such disturbances is readily realized. All intermediate stages between very quiet and extremely disturbed conditions exist.

Magnetic storms may be classified as having origin due (1) to changes occurring in the regions about the Earth, (2) to changes within the Earth, and (3) to changes within or external to the Earth and with center of field of action at times stationary but generally moving from place to place. Storms of the first type are simultaneous over the Earth. Frequently they are initiated by a sudden sharp shift following comparatively quiet or normal conditions and for this reason are called "sudden-commencement" disturbances. Sudden commencements seem always of an oscillatory character, and in general a tendency to oscillation and continual unrest is one of the most outstanding features. Fig. 21 reproduces the records of disturbed days at the Huancayo and Watheroo observatories, December 3–5, 1929. Fig. 21A shows records obtained on the same days at Little America, where the Institution cooperated with the Byrd Antarctic Expedition in maintaining a temporary magnetic observatory.

Storms of the second type are sometimes associated with great volcanic out-

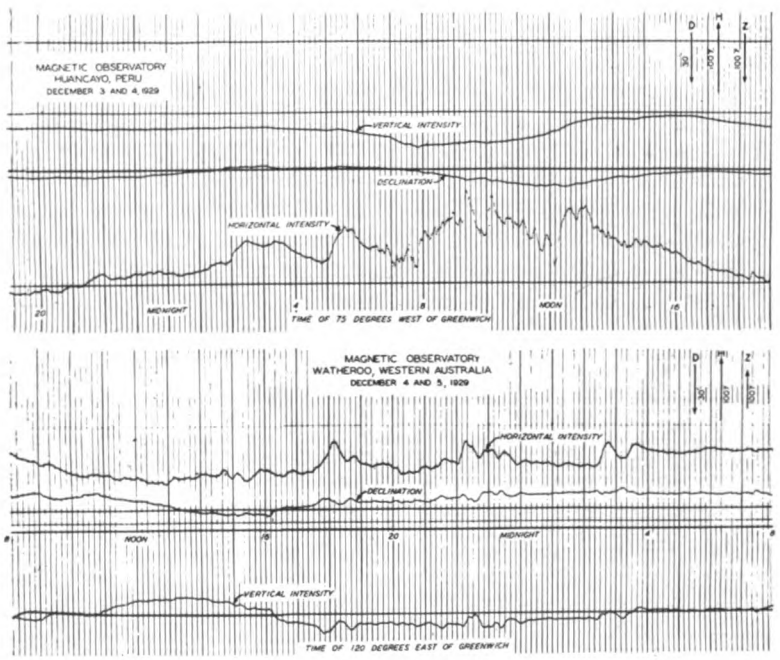


FIG. 21. MAGNETOGRAMS FOR TYPICALLY DISTURBED DAYS AT THE HUANCAYO AND WATHEROO MAGNETIC OBSERVATORIES, DECEMBER, 1929

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

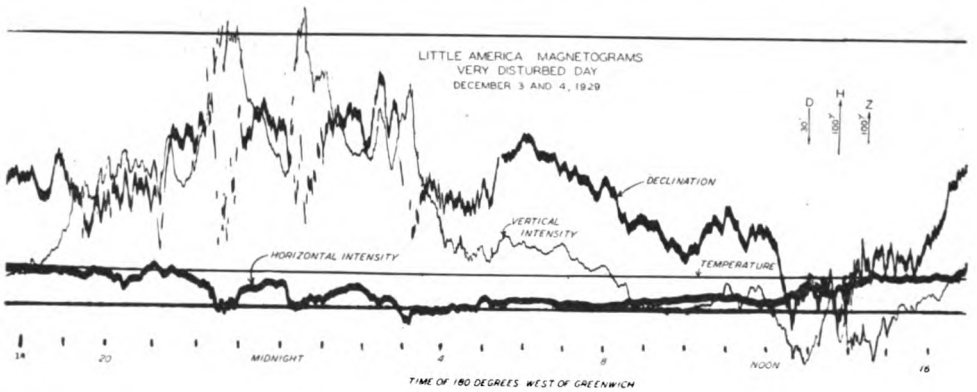


FIG. 21A. MAGNETOGRAM FOR TYPICALLY DISTURBED DAY AT LITTLE AMERICA, ANTARCTIC CONTINENT, DECEMBER, 1929

bursts as was the case for the eruption in Martinique in May, 1902, evidenced as world-wide by the magnetograms of many observatories. Fig. 22 reproduces records of the compass-directing magnetic force at 21 observatories. The third type is usually represented by a rather slowly developing "bay" on the record extending over a half-hour or somewhat more.

Thus disturbed or quiet magnetic conditions nearly always affect the whole Earth simultaneously. The possibility of any connection between disturbances of the Earth's magnetic field and the weather is excluded since weather is so distinctly local and so different all over the world. But polar lights—the aurorae—are always seen in polar regions when magnetic storms occur. See Figs 23, 23A and 23B for photographs of auroral displays of several types off Siberia. Since the height of polar lights has been determined to be in no case less than 50 miles above the ground, the conclusion is drawn that the magnetic variations and disturbances also have their origin in electrical phenomena taking place at least at greater heights in the atmosphere. This has been confirmed in every respect and the study of the magnetic variations is one of our main sources of information about the constitution of and the phenomena in these outermost and inaccessible regions of the atmosphere.

It was demonstrated in 1908 by Hale at the Mount Wilson Observatory of the Carnegie Institution that the Sun possesses a total magnetic field perhaps 50 times that of the Earth. But a field of that intensity is far too weak to make its magnetic influence felt at the Earth, 93,000,000 miles distant. It is much more probable that solar influences on the Earth's magnetism are connected with enormous streams or clouds of particles, atoms, ions, and electrons ejected from the active regions of the Sun, which travel through space and from time to time reach the Earth after one or two days, impinge its atmosphere, causing magnetic storms, which often disturb electrical communications. These particles, like the wave-radiations mentioned above, do not reach the Earth's surface but are stopped by the air before they come lower than 50 miles and cause inductively some of the observed effects in currents in the air and in the Earth. Thus one may conceive magnetic disturbance-features as the result of "messages from space."

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

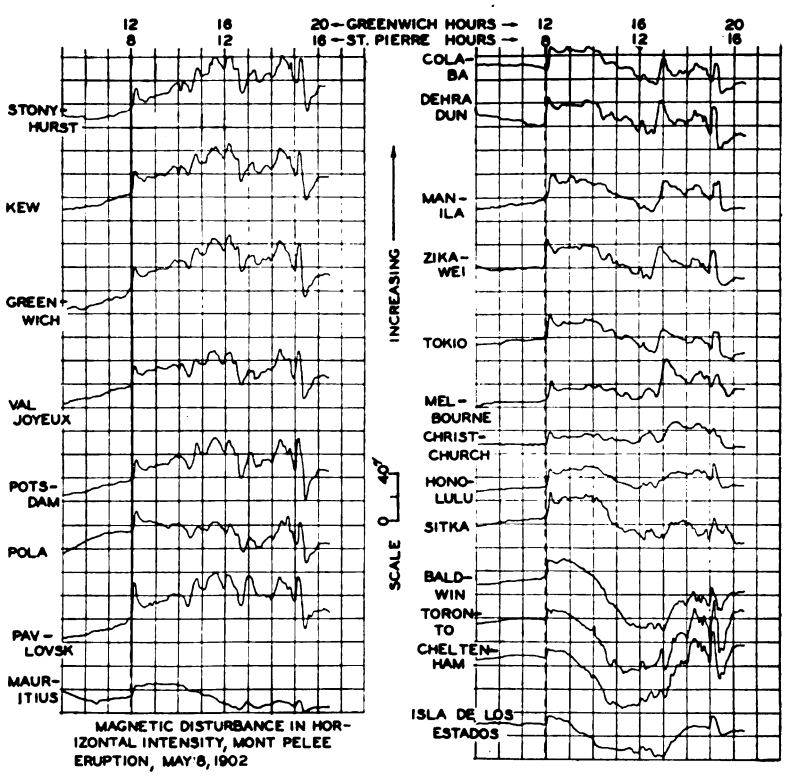


FIG. 22. SUDDEN-COMMENCEMENT MAGNETIC DISTURBANCE OF MAY 8, 1902, BEGINNING AT TIME OF MONT PÉLÉE ERUPTION

The regular daily magnetic variation apparently is the effect of other radiations from the Sun, which are absorbed in the highest levels of the air, and which make these layers electrically conducting. These conclusions drawn many years ago from magnetic observations became more important after the invention of wireless telegraphy, because with them we may explain why wireless waves are bent around the Earth along these same conducting layers.

The range of diurnal variation varies with magnetic character—a feature brought out in Fig. 24. Statistical studies have led to the identification of three phases in the progress of a disturbance, (1) strengthening of the ordinary diurnal movement according to local time, (2) everywhere a similar but unequal course according to universal time, and (3) a periodic damped wave dying out in the post-perturbation.

Magnetic activity provides one of the means of determining another time-change, namely, that of an 11-year period apparently agreeing with the well-known period in sunspot-frequency (Fig. 25). Latest investigations have shown, however, that solar activity as indicated in its reflected effect in the magnetic field is not completely or always represented by sunspottedness or other phenomena which astrophysicists observe on the Sun's surface; magnetic observations apparently reveal distinct solar influences of another kind and add in this way to our knowledge of solar physics.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

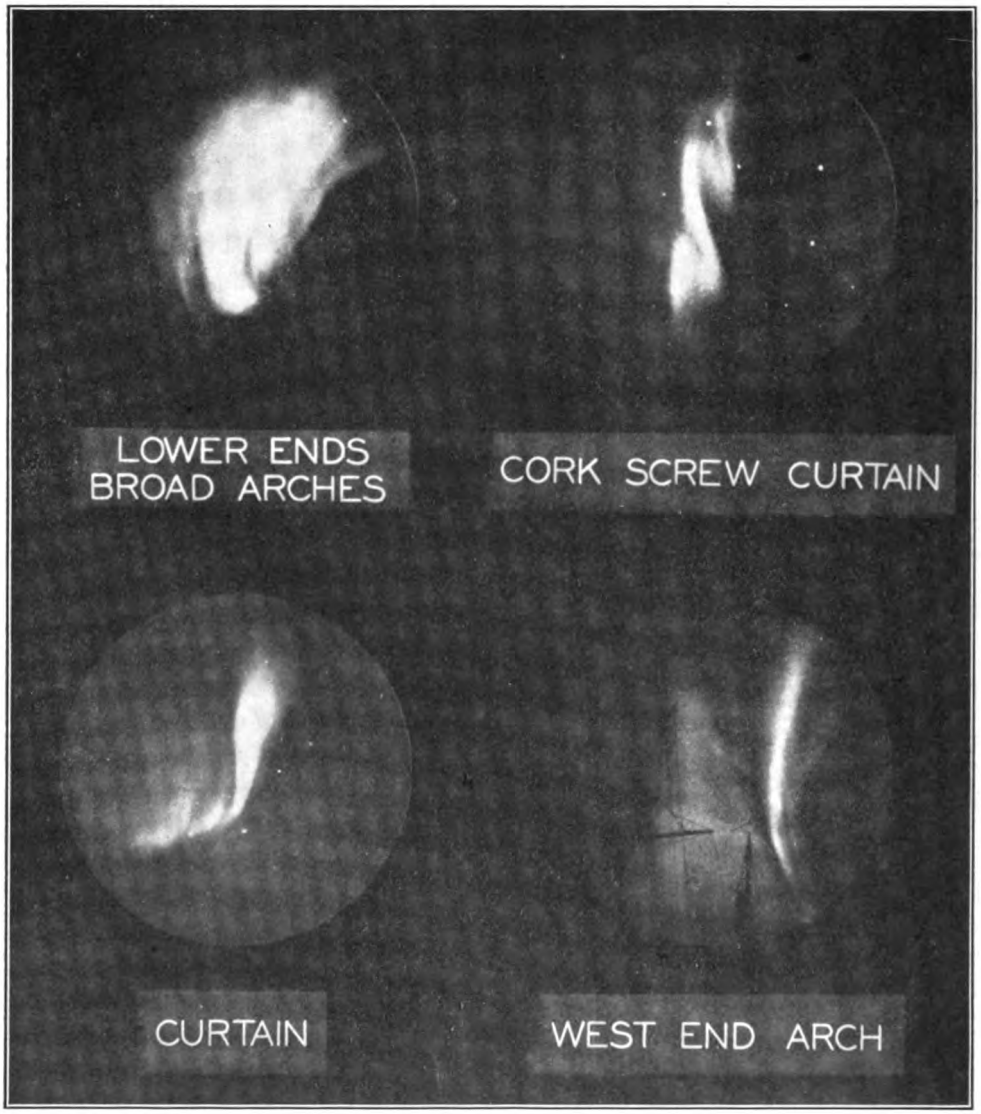


FIG. 23. TYPES OF AURORAL LIGHTS FROM PHOTOGRAPHS MADE OFF THE NORTH COAST OF SIBERIA

As the Earth revolves about the Sun during the year there are corresponding fluctuations in magnetic activity, the maximum or crest occurring during the equinoctial months of March and September, and the minimum or trough in the solstitial months of June and December. This annual variation of magnetic activity, shown by Fig. 26, was deduced from the examination of 59 years of observations, 1872–1930, at a number of observatories. The graphs result from grouping the data in thirds according to high, average, and low activity.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

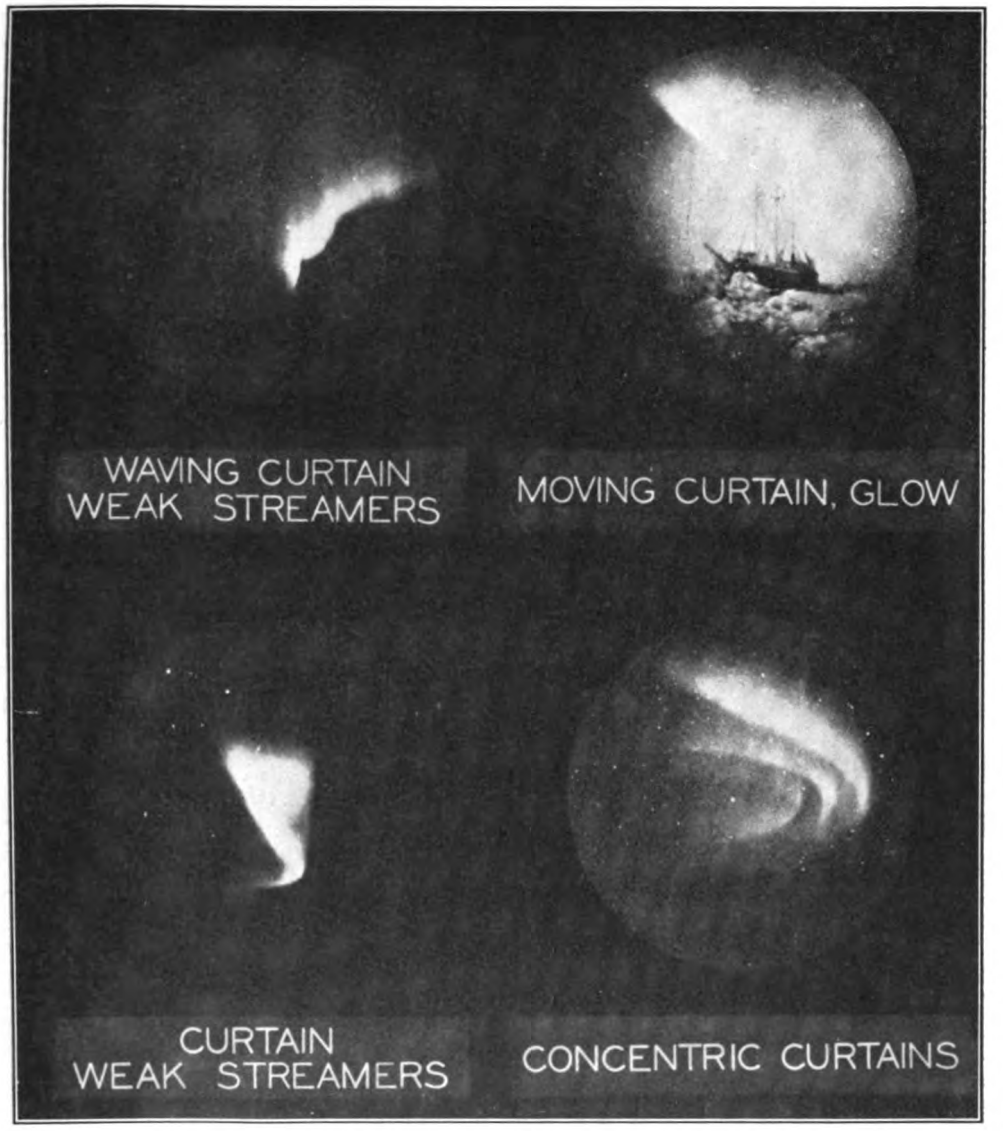


FIG. 23A. FURTHER PHOTOGRAPHS OF AURORAL LIGHTS

Another time-change related to magnetic disturbances is shown by Fig. 27, for an interval chosen at random, the consecutive averages of magnetic force over 24-hour intervals centered at 0^h, 6^h, 12^h, and 18^h Greenwich mean time for three widely separated stations—Seddin (near Potsdam, Germany), Huancayo (Peru), Watheroo (Western Australia). The three curves are strikingly similar showing typical depression during a disturbance followed by gradual recovery to normal value afterwards. Obviously the u-measure which is derived from

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

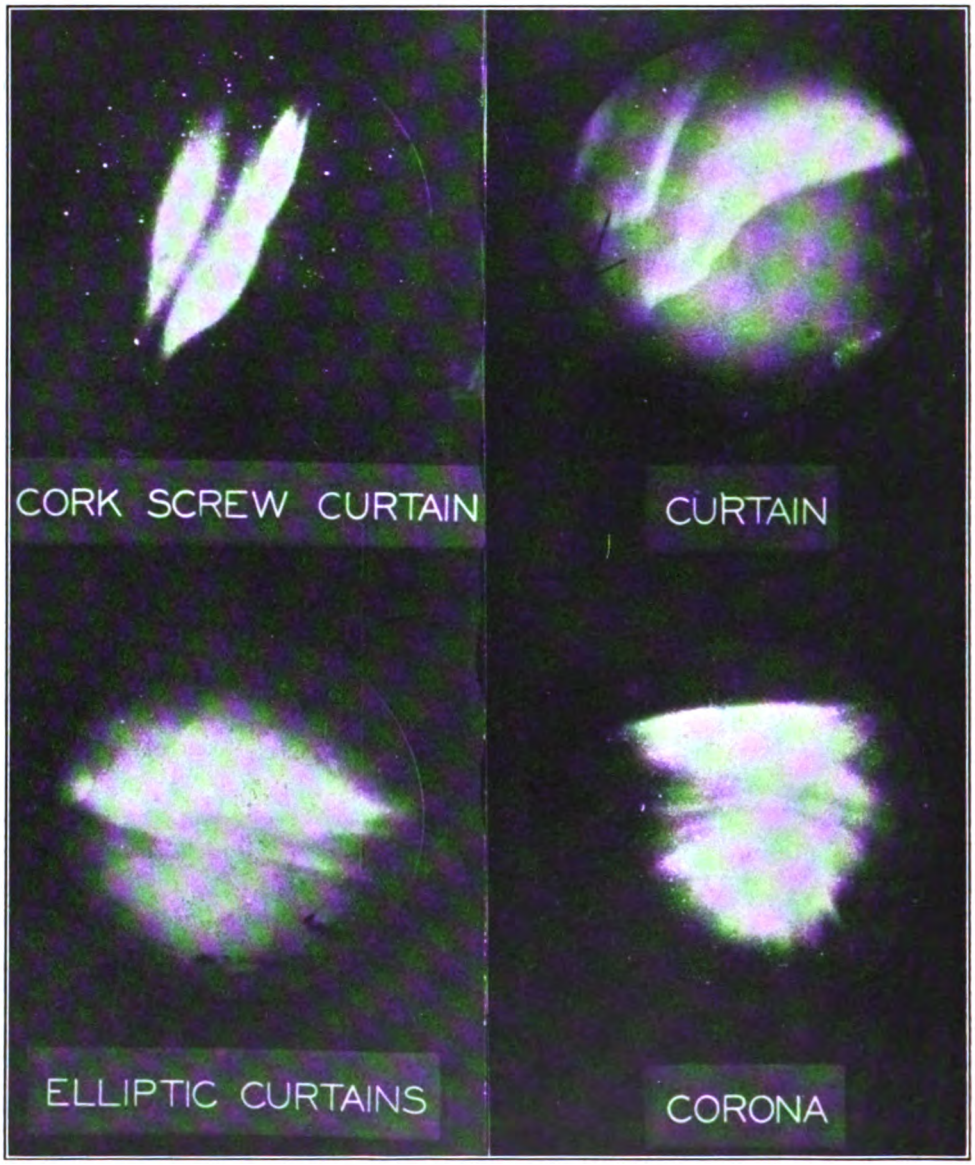


FIG. 23B. FURTHER PHOTOGRAPHS OF AURORAL LIGHTS

such systematic changes must be representative of the world-wide magnetic activity.

Pulsations

Another type of irregular disturbance is that known as micropulsations first noted by Eschenhagen and which appear to be of about the same magnitude at different locations on the Earth. These are of very short periods such as 5 to 15 seconds of time. It has been proposed (Störmer, 1906) that these short-period

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

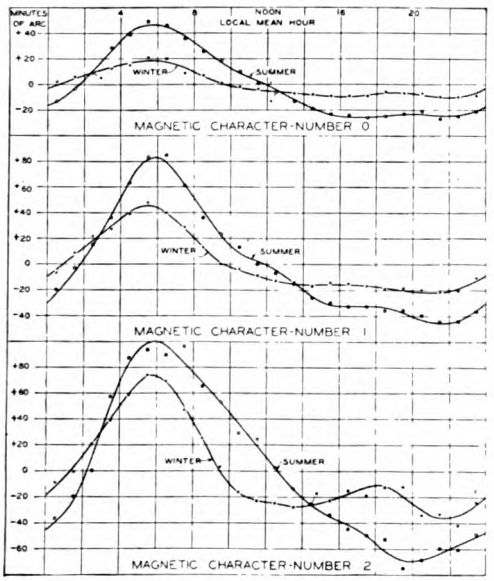


FIG. 24. CORRELATION BETWEEN DAILY VARIATION OF COMPASS-DIRECTION AND MAGNETIC ACTIVITY AT CAPE CHELYUSKIN, SIBERIA, OCTOBER, 1918, TO AUGUST, 1919

and small-amplitude pulsations may be explained in the world-wide sense as the electromagnetic effects of clouds of electrically charged particles moving in periodic orbits around the Earth. On the other hand, there are recorded at observatories in regions of comparatively limited area a giant type of pulsation with periods of as much as one and one-half to two minutes of time and ranges from 10 to 20 times as great. At the present time there is apparently such an area near Scandinavia. Fig. 28 shows records of giant pulsations obtained September 10 and 12, 1930, at Abisko, Swedish Lapland, and September 12, 1930, and September 19, 1931, at Tromsö, Norway. Tromsö is something over 90 miles north of Abisko. At two other observatories 215 and 370 miles, respectively, from Abisko the ranges recorded were considerably reduced, while they were found to be very minute or negligible at observatories distant about 1,000 miles or more. On account of the relatively local character of these giants, they can hardly be explained as suggested above for the normal small-amplitude pulsations. They may, therefore, reasonably be ascribed to peculiar currents now prevailing in the atmosphere above the northern part of Scandinavia or to a deeper penetration at times into the atmosphere there of Störmer's electrified "flying clouds." That such giant micropulsations are of local cause is indicated also since at other observa-

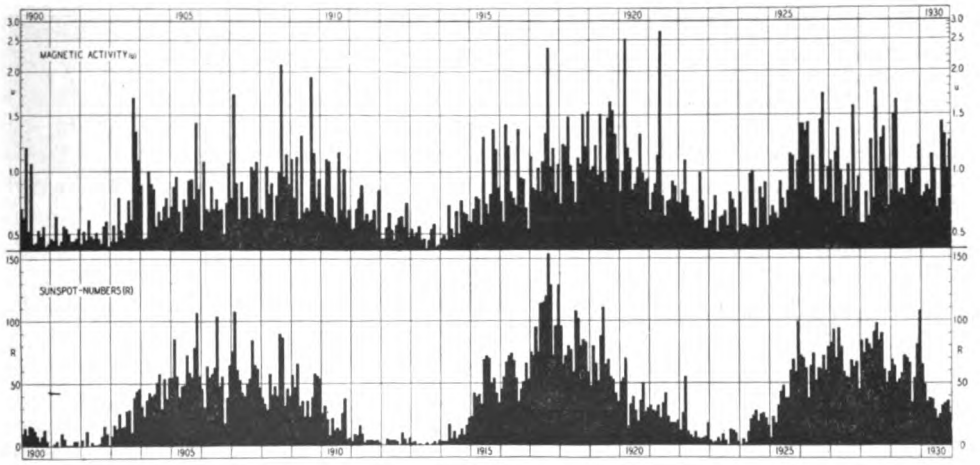


FIG. 25. MONTHLY MEANS OF MAGNETIC ACTIVITY AND OF SUNSPOT-NUMBERS, 1900–30

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

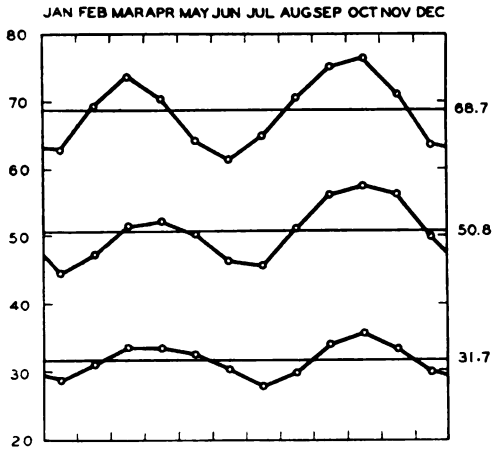


FIG. 26. ANNUAL VARIATION OF MAGNETIC ACTIVITY, 1872–1930, AVERAGED ACCORDING TO HIGH, AVERAGE AND LOW ACTIVITIES

tories they may be occasionally recorded for a period of years and then cease. Thus Professor Nippoldt at Potsdam, Germany, states that giant micropulsations "went to sleep" in 1903 and have since been very rare there.

CONCLUSION

This complexity of the magnetic time-change phenomena has baffled attempts at theoretical explanations or hypotheses although long the field of able and enthusiastic investigators. We may hardly hope in our time to lay down a general theory which will explain the multitude of observed facts or permit us to foretell with any precision future changes. Despite this, magnetic observations have already added materially to our knowledge of the Earth's interior, particularly to some of the geological features of its crust. Thus secular-variation changes within the crust indicate an interior

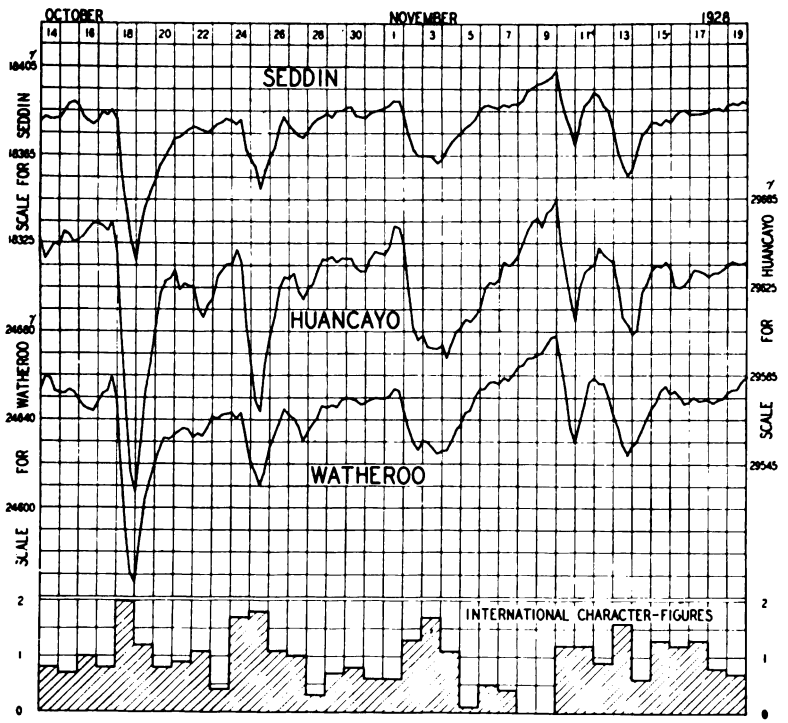


FIG. 27. TYPICAL DEPRESSION (POST-PERTURBATION EFFECT) FOLLOWING MAGNETIC DISTURBANCES AS SHOWN BY DATA FROM THE SEDDIN, HUANCAYO AND WATHEROO OBSERVATORIES, OCTOBER 14 TO NOVEMBER 19, 1926, WITH GRAPH OF INTERNATIONAL CHARACTER-FIGURES FOR THE SAME PERIOD

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

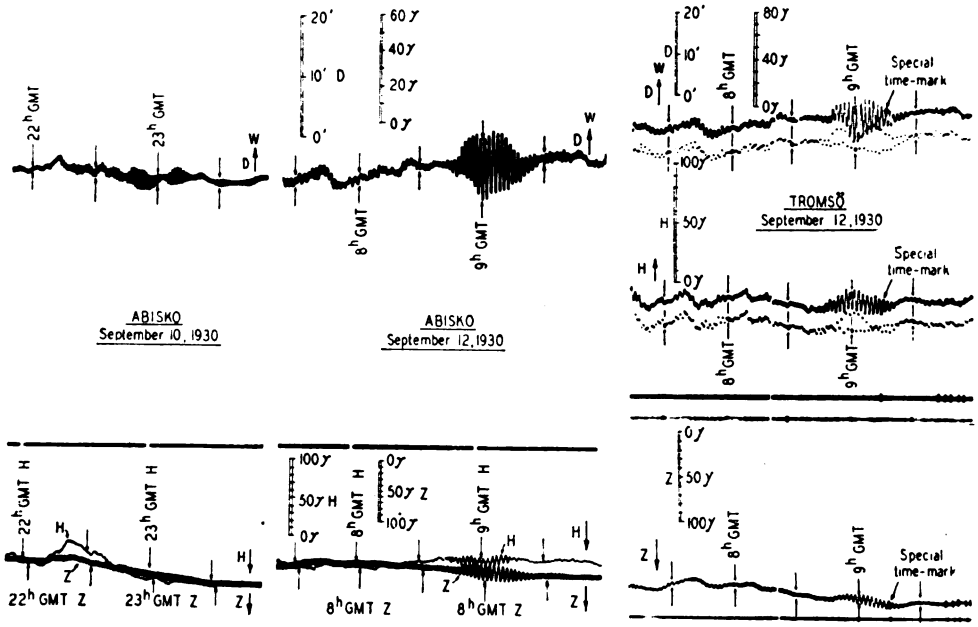


FIG. 28. RECORDS OF MAGNETIC PULSATIONS AT ABISKO AND TROMSÖ, SEPTEMBER 10, 12 AND 30, 1930

more mobile than the exterior layers, not only as a whole but regionally. Even more definite and promising are the results of those magnetic researches which give us also additional information regarding the high atmosphere above the Earth.

We must continue looking to observations and to their discussions perhaps more than to pure theory for further advance in knowledge of the causes and laws governing magnetic time-changes, as well as to provide foundations upon which tests may be made of theory. The rapid developments in physics and in atomic physics during the past decade, particularly in ionization, radioactivity, and high-vacuum electrical research, will permit speculations on the origin and changes of the Earth's magnetic field, which must materially advance fundamental conceptions of the nature and of the constitution of matter.

Some papers bearing on time-changes in the Earth's magnetic field are as follows:

L. A. Bauer, "Principal Facts of the Earth's Magnetism and Methods of Determining the True Meridians and the Magnetic Declination." Washington, D. C., U. S. Coast Geod. Surv., 100 pp. with illus. (1902). [Reprinted with slight changes, 1909, 1914, and 1919.]

D. L. Hazard, "The Earth's Magnetism." Washington, D. C., U. S. Coast Geod. Surv., Ser. No. 313, 52 pp., 1925.

J. A. Fleming, "The Magnetic and Electric Survey of the Earth: Its Physical and Cosmical Bearings and Development." *J. Wash. Acad. Sci.*, 16, 109–132 (1926).

G. Angenheister and J. Bartels, "Das Magnetfeld der Erde." Wien-Harms, *Handbuch der Experimentalphysik*, 25, I, 527–684, 1928.

L. A. Bauer, "Beiträge zur Kenntnis des Wesens der Säkular-Variation des Erdmagnetismus." (Dissertation, Univ. Berlin.) Berlin, Mayer und Müller, 54 pp., 1895.

H. W. Fisk, "Isopors and Isoporic Movements." Union Géod. Géophys. Internat., Sect. Mag. Electr. Terr., *Bull.* No. 8, 280–292, 1931.

A. Schuster, "The Diurnal Variation of Terrestrial Magnetism." Phil. Trans. R. Soc., A, 180, 467–518, 1889; 208, 163–204, 1908.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

W. van Bemmelen, "Die Lunare Variation des Erdmagnetismus." Met. Zs., 29, 218–230, 1912.

S. Chapman, "The Lunar Diurnal Magnetic Variation at Greenwich and other Observatories." Phil. Trans. R. Soc., A, 225, 49–91, 1925.

S. Chapman and A. T. Price, "The Electrical and Magnetic State of the Interior of the Earth, as Inferred from Terrestrial Magnetic Variations." Phil. Trans. R. Soc., A, 229, 427–460, 1930.

Terrestrial Magnetism and Atmospheric Electricity. An international quarterly journal. Published by the Johns Hopkins Press, Baltimore, Md. Volume 37 now in progress. Contains articles dealing with all branches of terrestrial magnetism and atmospheric electricity.

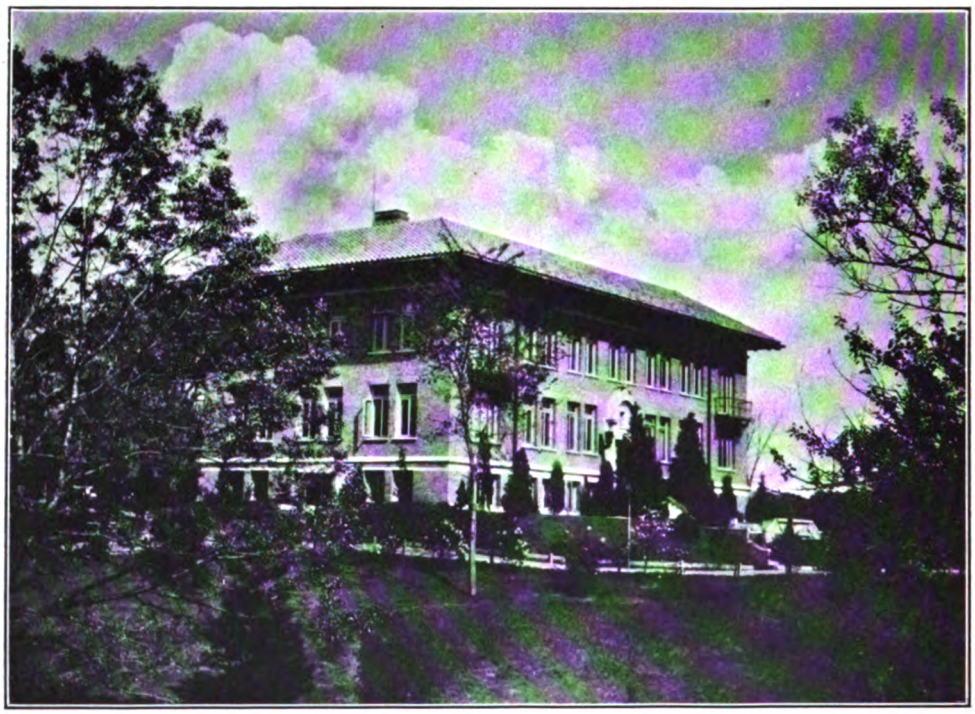


FIG. 29. LABORATORY OF THE DEPARTMENT OF TERRESTRIAL MAGNETISM, CARNEGIE INSTITUTION.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero

Digitized by Google

Original from UNIVERSITY OF MINNESOTA

COSMIC DISTURBANCES OF THE EARTH'S MAGNETIC FIELD AND THEIR INFLUENCE UPON RADIO COMMUNICATION[1]

By Dr. ARTHUR E. KENNELLY

PROFESSOR EMERITUS OF ELECTRICAL ENGINEERING, HARVARD UNIVERSITY AND THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY, RESEARCH ASSOCIATE, CARNEGIE INSTITUTION OF WASHINGTON

Purpose and Scope

It is hoped to show this evening that there are correlations, found by observation, to exist between (*a*) the strength of long-distance received radio signals, (*b*) changes in the apparent height of the ionized layers of the upper atmosphere, (*c*) changes in the Earth's magnetic field, and (*d*) disturbances on the surface of the Sun, as revealed by sunspots. Certain of these different phenomena are interconnected in recognized ways; but the reasons for the observed correlations between others are still mysterious. In order to solve these difficult cosmic problems, more numerous and more varied observations are needed, as to what is taking place in the upper atmosphere, and beyond. It appears, however, that by carefully studying the behavior of radio waves, directed experimentally skywards and received on the ground, after being reflected back from different elevations, it may be possible to throw light upon the nature and constitution of the otherwise inaccessible upper air.

The Ionized Layer or Layers in the Upper Atmosphere

In the early days of radio telegraphy, before the beginning of the twentieth century, it was supposed that when a simple radio impulse was started from a mast at a sending-station, a hemispherical electromagnetic wave was emitted from the mast as a center, like the upper half of a soap-bubble, expanding in all directions at the speed of light. The lower edge of this invisible hemisphere ran over the conducting surface of the ground or sea, in all directions, north, south, east and west, at the rate of 300,000 kilometers per second; while the top of the hemisphere shot upwards also at this speed. Only the lower edges of this wave, near the ground, could carry the impulse to receiving-stations. The electric energy in the upper portions of the hemisphere would be nearly useless for communication. This was the then generally accepted doctrine of three-dimensional expansion of radio waves.

When the Marchese Marconi came to North America in the late fall of 1901, to see if radio signals could be received from England across the North Atlantic Ocean, he was able to report receiving groups of dot-impulses caught in Newfoundland by a kite-lifted conductor, as emitted from his sending-station in Cornwall. The amount of energy required to operate the receiver was greater than should have been obtainable from the emission in England upon the three-dimensional hypothesis, and it was necessary to invoke some suggestion for preventing the heavy loss of energy upwards during transmission. It had been shown by Sir J. J. Thomson that highly rarefied air was capable of conducting electricity better than sea water, so that it was reasonable to assume that at an elevation of nearly 100 kilometers, the air was sufficiently rarefied to act as a conductor under the ionizing influence of

[1] The second in a series of three lectures concerning the magnetic field of the Earth and its atmosphere, delivered at the Carnegie Institution of Washington, March 15, 1932.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

powerful sunlight. It was known that the chemically active rays of the Sun, near the violet end of the spectrum, are able to ionize air, that is, to break up neutral gas atoms into electrically positive and negative constituents. The radio waves emitted from the sending-station would thus only expand hemispherically, until the ionized conducting-layer was reached, about 100 km above the station. Here they would be reflected back to the ground for repeated reflection upwards; so that the wave would then expand in two dimensions only, like a cart-wheel 100 km thick, the wave advancing radially, along the spokes.

This hypothesis of an ionized layer or layers in the upper air, prognosticated in 1902, was verified experimentally by Breit and Tuve, at the Department of Terrestrial Magnetism of the Carnegie Institution, who photographed in 1925 the arrival of radio echoes from the overhead ionized layer.[2] Thus this experimental verification by the highly analytical echo-method followed shortly the verification of Appleton and Barnett using their interference-method.

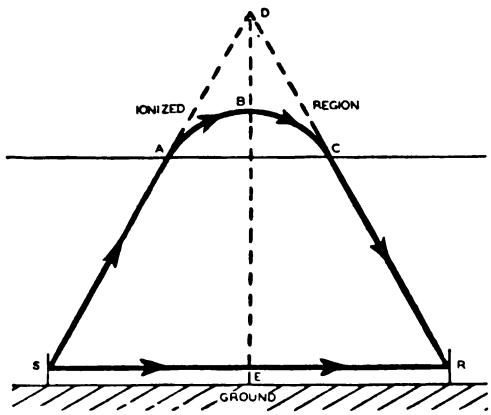


FIG. 1. DIAGRAM OF RAY-TRACK (AFTER APPLETON).

[2] G. Breit and M. A. Tuve, "A Test of the Existence of a Conducting Layer," *Phys. Rev.*, 28, 554–575, 1926.

[3] E. V. Appleton, "Some Notes on Wireless Methods of Investigating the Electrical Structure of the Upper Atmosphere," *Proc. Phys. Soc.*, 41, 43–59, 1928; 42, 321–339, 1930.

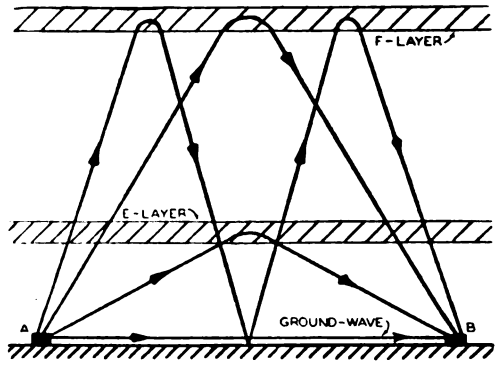


FIG. 2. VARIOUS PATHS BY WHICH PULSE MAY ARRIVE AT RECEIVING-STATION (AFTER GILLILAND AND KENRICK).

Fig. 1,[3] represents diagrammatically a radio sending-station S and a receiving-station R, situated on the ground-level SER, say 150 km apart. An outgoing radio impulse, emitted at S, reaches R over the ground, following the direct horizontal ground-path SER. This is called the "ground-wave." At almost the same moment, an upwardly directed ray SA reaches the ionized region ABC, the lower boundary of which is probably not sharply defined. On entering the region, the ray is bent from the straight path SAD into the refraction-path ABC, so that emerging from the ionized layer at C, it reaches the receiver R by the downward line CR. The up and down ray $SABCR$ will take a little longer to reach R than the ground-wave, and will reveal itself as an echo-signal following behind the ground-signal. The observed time of delay will furnish a measure of the apparent height, or virtual height, ED, of simple virtual reflection. This virtual height is greater than the actual height of the lower boundary AC of the layer, and also greater than the height EB reached by the ray before being turned back.

Fig. 2, from a recent paper by Gilliland and Kenrick,[4] indicates two ionized

[4] T. R. Gilliland and G. W. Kenrick, "Preliminary Note on an Automatic Recorder Giving a Continuous Height-record of the Kennelly-Heaviside Layer," *Bur. Stan. J. Res.*, 7, 783–789, 1931.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

layers, which Appleton has called the *E*- and *F*-layers, respectively. The *E*-layer is lower, and long radio waves tend to be reflected down to ground from it. Shorter waves can penetrate the *E*-layer, and may then be reflected down by the upper *F*-layer. The sending-station at *A* emits rays in all directions, including those along the ground. The ground-wave *AB* reaches the receiver at *B* by the direct route. A pulse is shown reflected from the lower layer *E*. There will be a certain short delay between the arrival at *B* of the ground-wave and the reflected *E*-wave. Then there is a wave shown which succeeds in passing through the *E*-layer twice, first upwards and then downwards, being reflected from the *F*-layer but not intercepted by the *E*-layer. This *F*-echo ray will have a greater delay than the *E*-echo. Finally, there is a pulse shown which is reflected from the *F*-layer to ground and then back from ground to sky, again reflected from the *F*-layer and reaching the receiver *B* after passing four times, in all, through the *E*-layer. In such a case, the photographic recorder at *B* would show one ground-pulse followed by three echoes, each of which has pursued a different path.

In some tests no echoes are found, and the ground-wave arrives alone. In others, one echo is found, while in yet

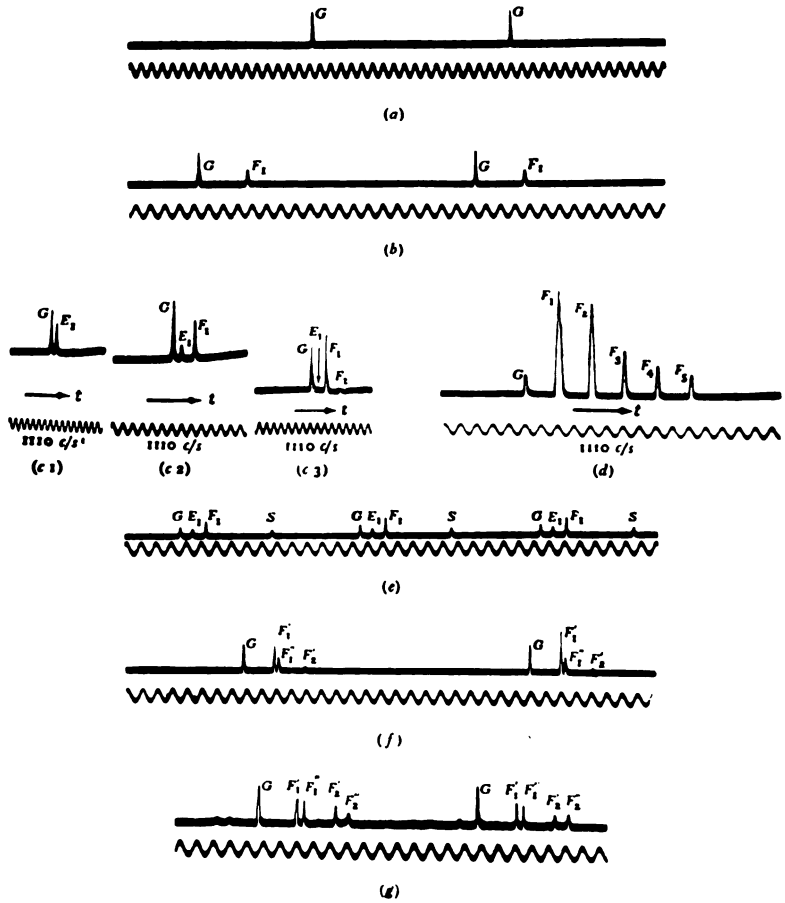


FIG. 3. DIFFERENT TYPES OF REFLECTION (AFTER APPLETON AND BUILDER).

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

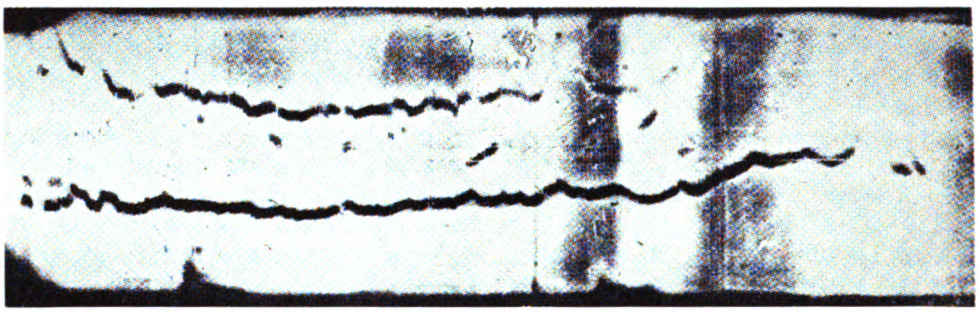


FIG. 4. HEIGHT-RECORD SHOWING GRADUAL RISE OF LAYER FROM 241 TO 399 KM, AND TEMPORARY APPEARANCE OF OTHER LAYERS; RECORD RUNS FROM 5: 30 P. M., JUNE 12, TO 2: 15 A. M., JUNE 13, 1931, FOR FREQUENCY 4,045 KC; THE GROUND-TRACE APPEARS AT BOTTOM OF RECORD (AFTER GILLILAND AND KENRICK).

others there may be six or more. In Fig. 3, which is taken from Appleton and Builder's paper[5] of January, 1932, there are various records of echo-patterns, obtained near London at different times. Time measurements are furnished by the serrated lines below each record, the frequency being given as 1,110 cycles per second; so that the interval between successive serrations is roughly one millisecond (0.0009 sec). The record at (*a*) shows only two successive ground-waves *G*, *G*, emitted about one fiftieth of a second apart, no echoes appearing. At (*b*) there are two records, each showing a ground-wave followed by one echo F_1, attributed to the *F*-layer, and arriving about 4 milliseconds (0.004 sec) later. If the delay were just 0.004 second, it would correspond to an extra length in the echo-path of $300{,}000 \times 0.004 = 1{,}200$ km, or to a virtual layer-height of approximately 600 km. At (*c*1) there is a ground-wave *G*, followed after about one millisecond by a single echo E_1 assigned to the E-layer. This delay would correspond roughly to a virtual layer-height of 150 km. At (*c*2) there is a ground-wave *G*, a small echo E_1 of about one millisecond delay from an *E*-layer, and then a larger echo F_1 of about 3 milliseconds' delay from an *F*-layer at a virtual height of about 450 km. At (*c*3) there is one very small *E*-echo and two *F*-echoes F_1 and F_2. At (*d*) there is no *E*-echo visible; but there are no less than four *F*-echoes at sensibly regular intervals. Similar echo-patterns, rather more complex, are given at (*e*), (*f*) and (*g*).

Similar oscillographic records have been made at the Department of Terrestrial Magnetism, by Tuve, Hafstad and Dahl.

Very recently, it has been found possible to obtain continuous photographic records of the virtual heights of the ionized layer or layers, by means of a special apparatus[4] designed for that purpose at the Bureau of Standards, under the direction of Dellinger. Such a record, covering a period of nearly nine hours, is given in Fig. 4. The ground-signals, forming a continuous heavy line, appear at the bottom of the record. There are then two curved lines, more or less parallel, indicating series of reflections from two virtual heights. There are also transient records of intervening layer-reflections. As the virtual height increases, so does the elevation of the corresponding curve from the base of the diagram.

[5] E. V. Appleton and G. Builder, "Wireless Echoes of Short Delay," *Proc. Phys. Soc.*, 44, 76–87, 1932.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

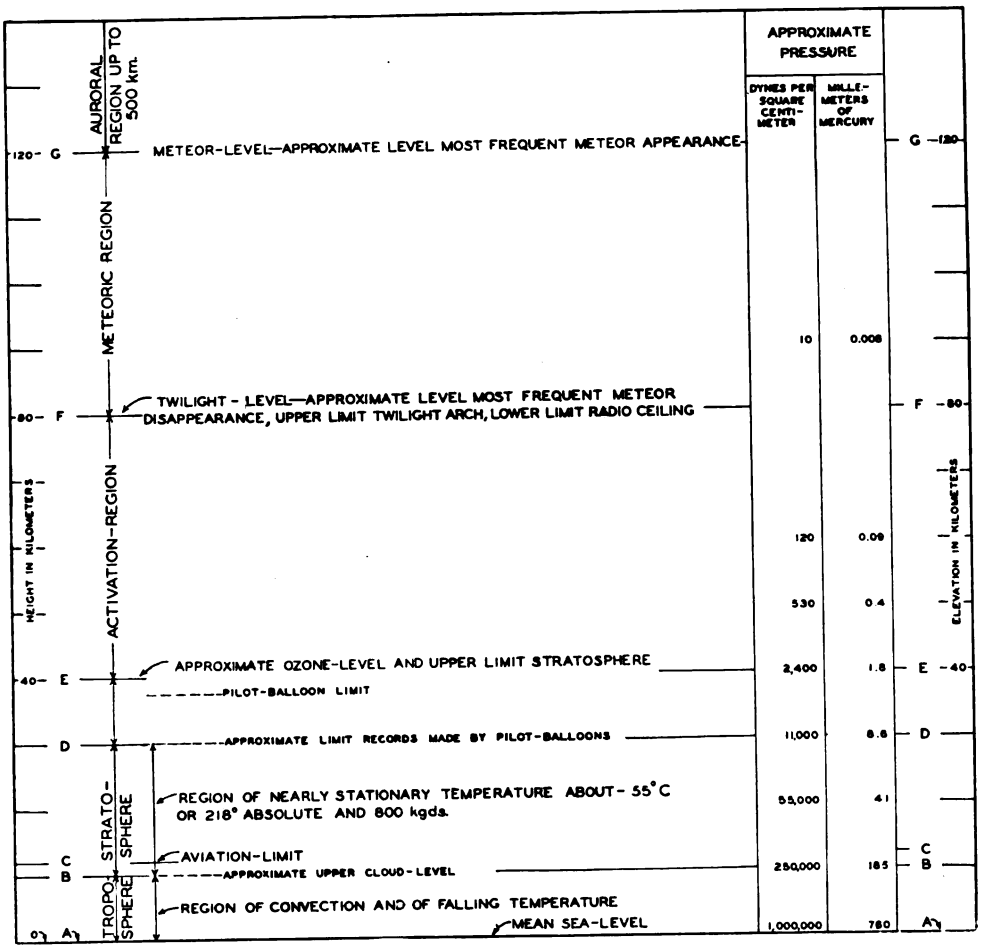


FIG. 5. OUTLINES OF ATMOSPHERIC REGIONS UP TO 120-KM ELEVATION (LEVELS *B*, *E* AND *F* ARE NOT FIXED, BUT ARE STATISTICAL AVERAGES VARYING WITH THE SEASON AND THE LATITUDE).

TROPOSPHERE, STRATOSPHERE, ACTIVATION, METEORIC AND AURORAL REGIONS OF THE ATMOSPHERE

A diagrammatic vertical section of the atmosphere, up to a height of 120 km, is given in Fig. 5, which has been prepared with the kind assistance of Professor Alexander McAdie, of the Blue Hill Meteorological Observatory. Here the bottom line *AA* represents mean sea-level. The level at *B*, 10 km up, gives the approximate upper limit level of clouds in the sky; while the 10-km layer *AB* is described as the *troposphere* or region above which the temperature ceases to fall and begins slightly to rise again. It will be understood that this dividing line between the troposphere and *stratosphere* varies with the latitude of the locality, season of the year and hour of the day, so that the elevation of 10 km is only a rough round number easily remembered. The other levels at *E*, *F* and *G* are likewise only averages.

At or near 12 km, *C* in the diagram, is the approximate limit of aviation height. At *D*, 30 km up, is the approximate limit of elevation from which rec-

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

ords have been secured by apparatus sent up on "pilot-balloons"; while at 37.5 km we have the limit of non-recording pilot-balloons.

At *EE,* 40 km elevation, we have the approximate upper limit of the stratosphere and the estimated "ozone-level." From *EE* to *FF,* we have an activation region in which ionization is supposed to develop actively during daylight hours. At *FF,* 80 km above the sea, is the twilight level. Near here is the upper limit of the twilight arch in the sky, the most frequent level of meteor disappearance, the lower level of the lower ionized layer or *E*-layer of Appleton's observations, and also the lower limit of auroral displays.

Between the 80-km and 120-km levels *FF* and *GG,* is the meteoric region, in which meteors are most abundantly visible. Above the meteor average appearance—level *GG,* extends the auroral region, and the region of upper ionization up to say 500 km. Above the 30-km level, however, from which direct records have been secured, information concerning the nature and constitution of the upper air is at present necessarily fragmentary and indirect.[6]

Correlation of Long-wave Transatlantic Radio Signal-strengths with Terrestrial-magnetic Fields, and with Sunspots

In Fig. 6 there is seen a plotted series of observations of monthly average radio signal-strengths over a period of seven years (1921–28), emitted by Lafayette station, and recorded (heavy line) at the Bureau of Standards in Washington, by Austin, and (dotted line) at the Meudon Observatory, near Paris, France. The Lafayette station is close to the Bay of Biscay shore, near Bordeaux, France, and its conditions of signal-emission are reported at regular intervals. It will be seen that there is good correlation between these curves, which rise and fall together. These 3 P. M. (Eastern Standard Time) signals are strongest each year in the winter and weakest in the summer months. The ratio of annual low to high is smaller at Meudon than at Washington, D. C. The direct path of transmission is entirely overland to Meudon, across France; while it is almost entirely over the sea, to Washington, across the Atlantic Ocean. Here the annual fluctuations may be partly cosmic, that is, produced by influences outside the Earth's surface, and partly terrestrial, or by influences at or within the Earth's surface; but the effects are similar in both series of observations.

Photographic records of the elements of the Earth's magnetic field, as obtained at Cheltenham, Maryland, have been maintained by the U. S. Coast and Geodetic Survey for many years, and a daily record of the strength of radio signals from several European long-wave radio stations has been maintained by Austin at the Bureau of Standards for 17 years. Austin's comparison between the magnetic activity in horizontal-intensity component and radio signal-intensity is presented in Fig. 7. It shows a fair degree of correlation. It is not yet

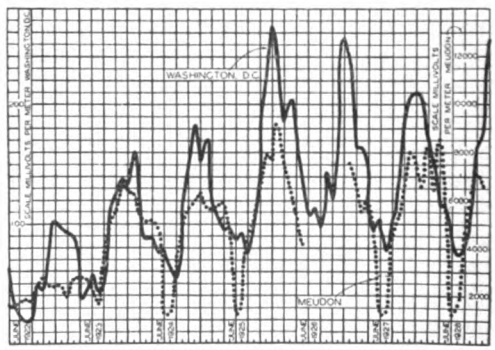


FIG. 6. MONTHLY AVERAGE SIGNAL-INTENSITY AS RECEIVED FROM LAFAYETTE STATION (FYL) AT WASHINGTON AND AT MEUDON, 3 P. M. (AFTER AUSTIN).

[6] Alexander McAdie, "Observations and Investigations Made at the Blue Hill Meteorological Observatory in 1929," Cambridge, 1930.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

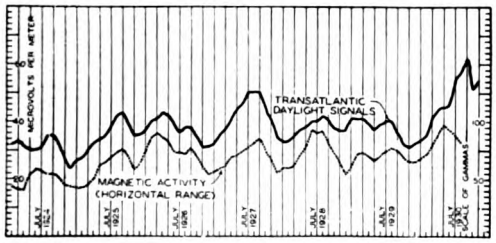


FIG. 7. CORRELATION BETWEEN MAGNETIC ACTIVITY AS INDICATED BY RANGE IN HORIZONTAL INTENSITY AT CHELTENHAM, MARYLAND, AND RECEPTION-INTENSITY OF TRANSATLANTIC DAYLIGHT SIGNALS (AFTER AUSTIN).

clear as to the nature of this correlation. It may be attributable in part to variation in the ionized layer, the radio ceiling over the Atlantic Ocean, or to cosmic influences not yet grasped. In this case, the radio signals were received from Europe in an east-west direction. A similar analysis by Austin for signals from Argentina, received over the Atlantic in a south-north direction, as given in Fig. 8, for the four years 1924–28, seems to show but little correlation; so that apparently the direction of transmission enters into the relation.

A set of curves appears in Fig. 9 for

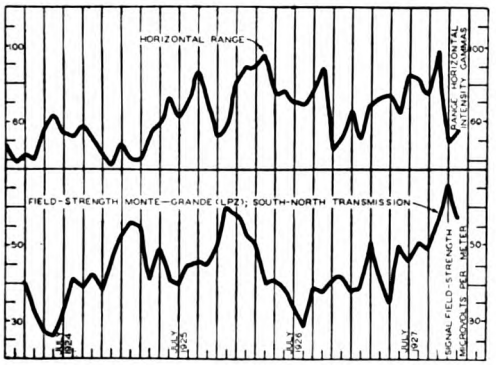


FIG. 8. CURVES OF MAGNETIC ACTIVITY AS INDICATED BY RANGE IN HORIZONTAL INTENSITY AT CHELTENHAM, MARYLAND, AND RADIO SIGNAL-STRENGTH FROM STATION MONTE GRANDE (LPZ) IN ARGENTINA, SHOWING LACK OF CORRELATION ON NORTH-SOUTH RECEPTION (AFTER AUSTIN).

three series of observations—(*a*) radio signal-intensity, averaged from several European stations, as measured at the Bureau of Standards, (*b*) sunspot-numbers and (*c*) the solar radiation-intensity as measured by the Smithsonian Institution, all for a period of three years. Here we have very distinct correlation between the three curves. Some interrelation exists between these solar variations and radio variations. Perhaps it is attributable to the conditions of the ionized layer.

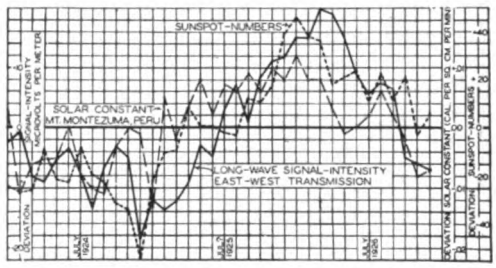


FIG. 9. CORRELATION BETWEEN SUNSPOT-NUMBERS, SOLAR RADIATION AND SIGNAL-INTENSITY AS RECEIVED AT WASHINGTON, 10 A. M. AND 3 P. M., FROM EUROPEAN STATIONS DURING JANUARY, 1924, TO DECEMBER, 1926, AS REPRESENTED BY THE DEVIATION OF MONTHLY AVERAGE FROM 3-YEAR MONTHLY AVERAGES (AFTER AUSTIN).

Fig. 10, from Austin's comparison of monthly averages for radio signal-intensity from two European stations, and for monthly averages of sunspots, is plotted over a six-year period. Here we recognize a general correlation, but without close agreement in detail.

We now come to some comparisons by Pickard (Fig. 11) over an eight-year period 1916–24 between averages of radio signal-intensities from the European station Nauen, as observed at the Bureau of Standards, and terrestrial-magnetic variations. Here again we find a certain degree of evident correlation, although in details the agreement is not close.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

Correlation of Sunspots with Radio Signal-strengths of Moderate Wave-length

We have thus far been discussing the behavior of long radio waves relative to sunspots or to terrestrial-magnetic variations. For present purposes, we may define long waves as waves exceeding one kilometer in length. We may now consider the behavior of moderately long radio waves (100 meters to 1,000

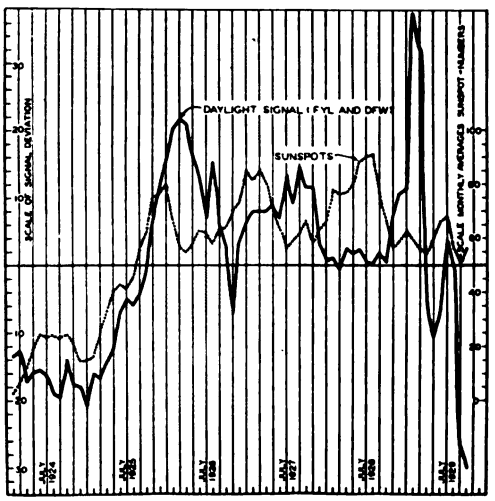


Fig. 10. Signal deviations of monthly signal-strength from 6-year monthly averages compared with monthly averages of sunspot-numbers, January, 1924, to October, 1929 (after Austin).

meters). American broadcasting-stations employ moderately long waves (200 meters to 550 meters). Pickard and Stetson have made records of the radio carrier-wave intensities from certain broadcasting-stations, and have compared them with sunspot-numbers during the same period. Fig. 12 is a diagram given by Stetson, of the Perkins Astronomical Observatory, for the evening radio reception from station WBBM of Chicago, plotted upwards during the three years 1926–28, and for the sunspot-numbers plotted downwards during the same period. Here a distinct inverse correlation is indicated. Similar results have been reported by Stetson during a more recent period.

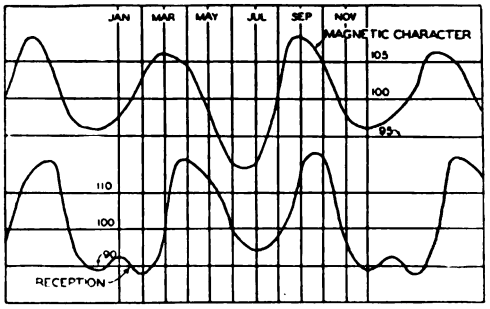


Fig. 11. Monthly averages of magnetic character of day and Washington day reception from station POZ, 1916 to 1924 (after Pickard).

Diurnal Range of Virtual Height of Ionized Layer on Magnetically Quiescent Days

It is found that the virtual height of the ionized layer for short waves, that is, waves of from 10 meters to 100 meters in length, goes through a fairly regular diurnal variation in the absence of magnetic storms or perturbations. In general, the height is lower during daylight than during darkness, although the conditions vary in detail with the season and the locality. An explanation for this observed condition is suggested by the fact that during sunlit hours the upper air is exposed to active ionization by the Sun's rays, especially at the violet end of the spectrum; so that the number and den-

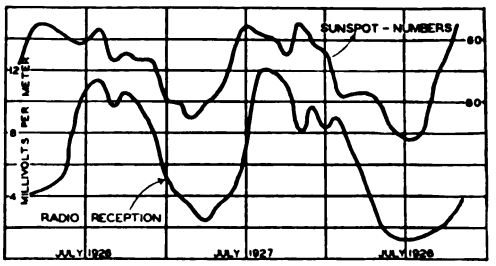


Fig. 12. Correlation between sunspot-numbers and signal-intensity, 1926 to 1928 (after Stetson).

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

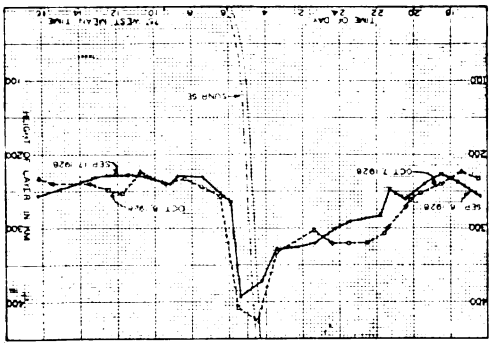


FIG. 13. DIURNAL VARIATION IN HEIGHT OF THE KENNELLY-HEAVISIDE LAYER ON TWO DAYS, SEPTEMBER 16–17 AND OCTOBER 7–8, 1928, FOR WAVE-LENGTH OF 70 METERS (AFTER TUVE, HAFSTAD AND DAHL).

sity of free electrons considerably increase, thus bringing the ionized layer lower. At night, on the contrary, neutralization of the gas atoms tends to occur, by the attraction between free electrons and ions.

Fig. 13 shows the range of virtual heights observed at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, for waves of 67.5-meter length, on two days, namely, September 16 and October 7, 1928. During the daytime the virtual height of the ionized layer was about 225 km; but this increased at night to about 400 km just before sunrise.

A pair of curves of diurnal layer-height appear in Fig. 14 for the day October 7–8, 1928, as observed concurrently at two different American receiving-stations. The waves of 67.5-meter length were emitted at the Bellevue Naval Research Laboratory, near Washington, D. C. The heavy curve shows the virtual heights as measured by Kenrick and Jen at the Moore School of Electrical Engineering in Philadelphia,

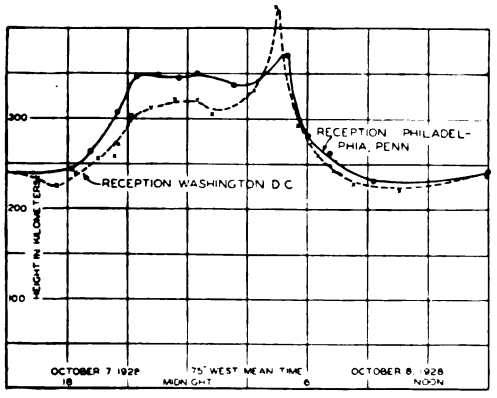


FIG. 14. VIRTUAL HEIGHTS OBSERVED OCTOBER 7–8, 1928: (*a*) AT MOORE SCHOOL OF ELECTRICAL ENGINEERING IN PHILADELPHIA, PENNSYLVANIA, (*b*) DEPARTMENT OF TERRESTRIAL MAGNETISM, WASHINGTON, D. C., ON TRANSMISSION FROM NAVAL RESEARCH LABORATORY, WASHINGTON, D. C., ON 4,435 KC (AFTER KENRICK AND JEN).

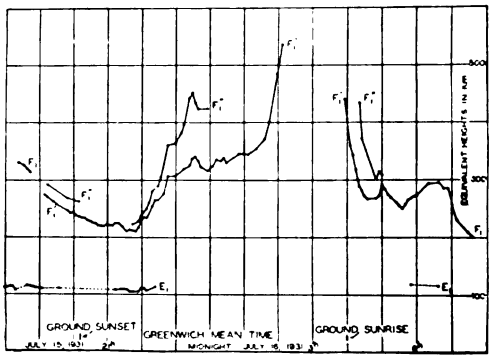


FIG. 15. LAYER-HEIGHTS AT DIFFERENT HOURS (AFTER APPLETON).

while the dotted line shows the heights measured at the Department of Terrestrial Magnetism, Washington, D. C., by Tuve, Hafstad and Dahl. The two curves are in good conformity. The daylight height was about 225 km and the darkness height about 400 km before sunrise.

Fig. 15 is taken from a recent paper by Appleton. It represents the virtual layer-heights measured at King's College, London, for waves of 80-meter length, during the day July 15–16, 1931, emitted from a sending-station in East London. Appleton points out that, during part of the time, reflections were obtained from the *E*-layer at a height of

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

about 110 km, as well as from a higher *F*-level. During the night, however, the *E*-reflections disappeared and the virtual height of the *F*-level rose to 500 km, when finally this layer disappeared until about sunrise.

A radio wave emitted near the ground from a simple vertical mast antenna is observed to be plane polarized, that is, its electric flux oscillation is in a vertical plane (following the electric current oscillations in the antenna); while the associated magnetic flux oscillation is in the horizontal plane of the ground.

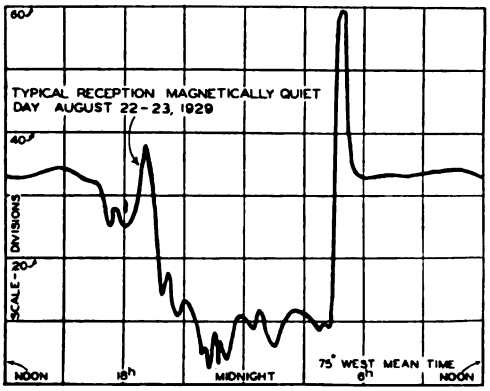


FIG. 16. TYPICAL RECEPTION FROM TUCKERTON (WCI) AT NEWTON CENTER, 16-KM WAVE, ON MAGNETICALLY QUIET DAY, AUGUST 22–23, 1929, SHOWING MARKED SUNSET AND SUNRISE PEAKS AND LOW NIGHT FIELDS (AFTER PICKARD).

Appleton finds that when such a wave passes through an ionized layer in a direction roughly parallel to the Earth's local magnetic field, the wave tends to split into two rotary polarized components, one right-handed and the other left-handed. In the northern hemisphere, the former is retarded and absorbed by the layer more than the left-handed one; so that the received descending wave is found to be circularly polarized with left-handed rotation. In a recent[7] communication, he has described

[7] E. V. Appleton, "Polarization of Downcoming Wireless Waves in the Southern Hemisphere," *Nature*, 128, 1037, 1931.

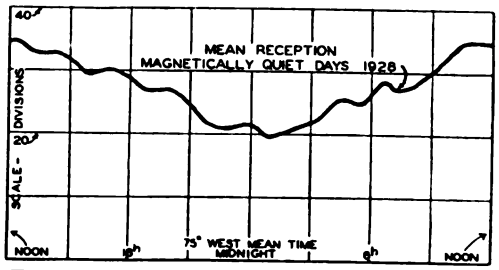


FIG. 17. TYPICAL RECEPTION FROM TUCKERTON (WCI) AT NEWTON CENTER, 16-KM WAVE, FOR THE MEAN OF MAGNETICALLY QUIET DAYS IN 1928 (AFTER PICKARD).

experiments made in Australia, not remote from the magnetic pole of the southern hemisphere, and there the reflected wave has been found to possess right-handed circular polarization. Perhaps the two *F*-layer reflections in Fig. 15 correspond to the two rotary components into which the initial wave may be thus decomposed.

EFFECTS OF MAGNETIC STORMS ON LONG-RANGE RADIO SIGNAL-RECEPTION

It is found that magnetic storms, as recorded in terrestrial-magnetic observatories, are not only apt to be accompanied by powerful stray currents in the crust of the Earth and by auroral displays in the upper air, but also by marked disturbances in radio signals, although the effect produced differs with the length of the radio waves.

Fig. 16 is a graph given by Pickard of diurnal signal-strength received at Newton Center, Massachusetts, on fairly

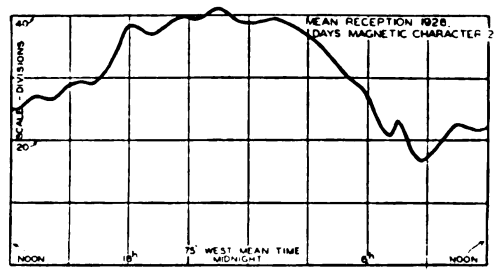


FIG. 18. TYPICAL RECEPTION FROM TUCKERTON (WCI) AT NEWTON CENTER, 16-KM WAVE, FOR THE MEAN OF DAYS OF MAGNETIC CHARACTER 2 DURING 1928 (AFTER PICKARD).

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

long radio waves emitted from the Tuckerton Station WCI, during a single magnetically quiescent day, August 22–23, 1929. Here the received intensity is fairly steady during the day, falls to a somewhat irregular low value at night, and shows sudden peaks near sunrise and sunset.

Pickard's corresponding graph for average reception during six months at and from the same stations on days of moderately quiet magnetic conditions appears in Fig. 17. There is now relatively little difference between day and night signal-intensity. The peaks have disappeared.

The conditions of diurnal average reception for days of magnetic disturbances or moderate magnetic storms are given in Fig. 18. Here the received signal-intensity at Newton Center is greater at night than by day, or there is a reversal of the quiescent conditions. Finally, Fig. 19 is Pickard's graph for reception-conditions during the severe magnetic storm of July 8–9, 1928. Here the signal-intensity is very distinctly greater during the night than during daylight hours, showing a marked inversion of the conditions existing on magnetically quiet days.

In Fig. 20 we have some graphical analyses reported by Anderson, of the American Telephone and Telegraph Company, for the radio signal-intensities of long transatlantic waves, in the year 1927. The central line of each diagram represents the onset of the storm, and

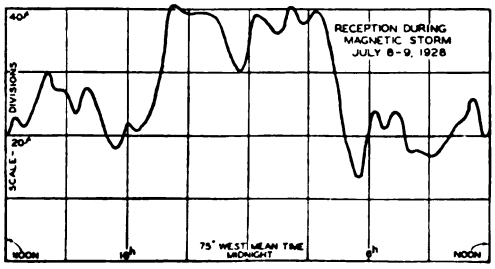


FIG. 19. TYPICAL RECEPTION FROM TUCKERTON (WCI) AT NEWTON CENTER, 16-KM WAVE, DURING SEVERE MAGNETIC STORM JULY 8–9, 1928, SHOWING MARKED INVERSION (AFTER PICKARD).

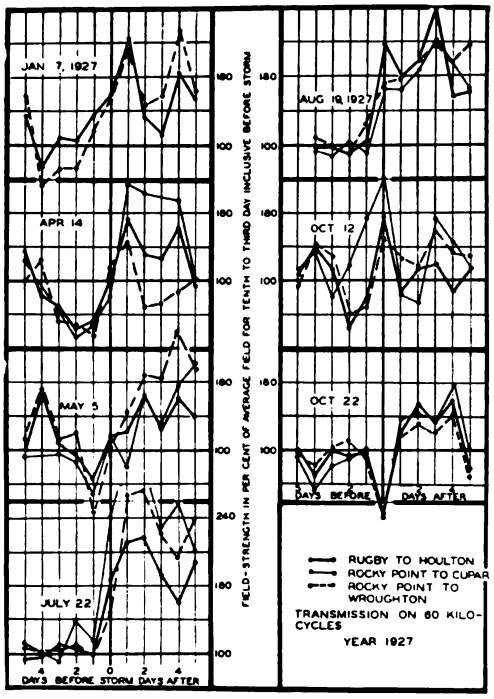


FIG. 20. EFFECT OF SOLAR DISTURBANCES ON 60-KC/S DAYLIGHT RADIO TRANSATLANTIC TRANSMISSION IN 1927, SHOWING CORRELATION OF LONG-WAVE RADIO RECEPTION AND MAGNETIC STORMS (AFTER ANDERSON).

seven storms are separately considered. The mean signal-strength is plotted for each of the five days before and after the storm, on three distinct radio transmissions. The curves tend to show that for these long waves (5 km), the signal-strength increased distinctly for a few days after a storm.

A similar result is reached in Fig. 21, which represents an analysis by Austin and Wymore for the signal-strength received at the Bureau of Standards during the years 1925–27 from several long-wave European stations. The deviations attributable to magnetic storms are plotted for five days before and after the onset. There is a distinct rise in signal-strength following a storm, reaching a maximum in about two days and falling back to normal in about three days more.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

On the other hand, the effect of a magnetic storm on the reception of short radio waves crossing the Atlantic, seems to weaken them greatly. Anderson's analysis of the effect of a magnetic storm on July 8, 1928, appears in Fig. 22. The thin broken line indicates the variation in the horizontal component of the Earth's magnetic field; while the heavy line indicates the strength of short-wave radio transmission from Deal, New Jersey, to New Southgate in England. These two lines follow together remarkably. They show a falling off in radio reception commencing two days before the center of the storm, reaching a minimum at the time of greatest magnetic disturbance, and returning to normal after about six days. At the same period, the long-wave radio signals (5,000 meters) from Long Island, New York, to Cupar in Scotland, increased instead of dwindling, during and after the storm.

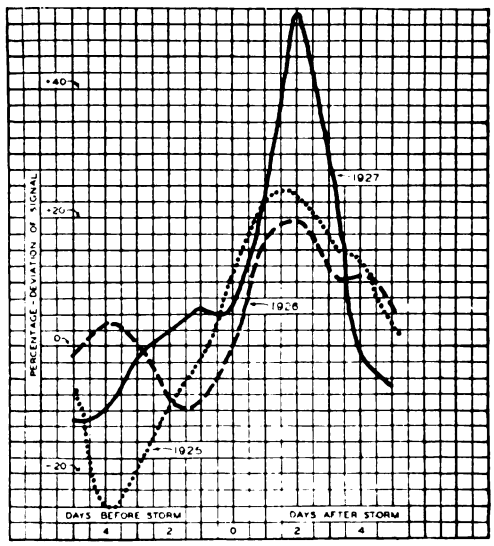


FIG. 21. AVERAGE DAILY DEVIATION FROM MONTHLY MEAN OF DAYLIGHT FIELD-STRENGTH OF SIGNALS FROM STATIONS IN EUROPE DURING PROGRESS OF MAGNETIC STORMS 1925, 1926, 1927 (AFTER AUSTIN AND WYMORE.)*

* Note correction in Fig. 21: The dotted-line curve should be dated 1926, and dashed-line curve 1925.

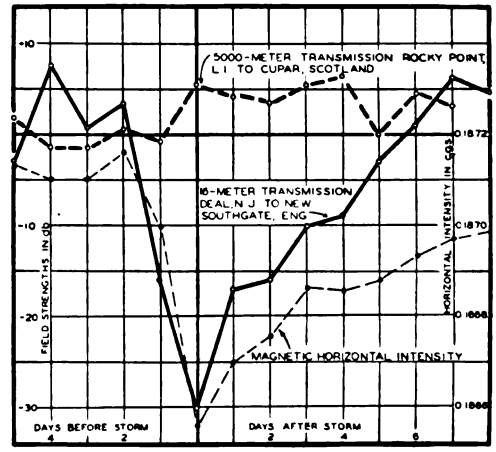


FIG. 22. VARIATION IN RADIO TRANSMISSION FOR 16-METER AND FOR 5,000-METER TRANSATLANTIC SIGNALS, SHOWING CORRELATION WITH MAGNETIC STORMS (AFTER ANDERSON).

Although there is little known, as yet, concerning the influence of magnetic storms on radio wave-transmission, yet the suggestion has been offered by several observers that during magnetic storms there is likely to be an increase in the depth and density of the ionized layer. This tends to improve the reflection and transmission of long waves. On the other hand, the short waves which are supposed to be reflected back to ground from higher levels, are likely to suffer excessive attenuation, by absorption in the lower layers.

SUNSPOT-CYCLES AND CYCLES OF TERRESTRIAL-MAGNETIC ACTIVITY

That there is a clear correlation between sunspot-cycles and cycles of the Earth's magnetic activity is borne out by Fig. 23, which compares annual sunspot-numbers with corresponding annual magnetic activity, as tabulated at the Department of Terrestrial Magnetism, over the period 1834–1930 or nearly 100 years. The upper curve follows the magnetic activity, and the lower the sunspot-numbers. Although the details of these curves often differ, yet the general agreement is remarkable. There appear to have been 8 com-

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

plete cycles of each of these two curves, between the peaks of 1837 and 1928, or an average of about 11.4 years per cycle. Why the Sun should exhibit an eruptive habit of this period is still mysterious. It has been suggested that possibly both series of phenomena may be concurrent symptoms of cosmic influences even more remote than the Sun. At the present date (1932), we are descending to an expected minimum of both sunspots and magnetic activity due in or near 1934.

Two theories have been advanced for the correlation between spots on the Sun with magnetic changes, as well as ionized-layer and radio disturbances on the Earth. These two theories are perhaps not mutually exclusive. One emphasizes the ejection of finely divided matter from the surface of the Sun in jets, which move outwards at high speeds, and, if favorably directed, may reach the Earth's atmosphere in such a manner as to set up strong electric currents, auroral discharges, ionization, etc. The other emphasizes the action of ultra-violet light emitted from the sunspots and the ionizing influence[8] of this actinic radiation on the Earth's atmosphere.

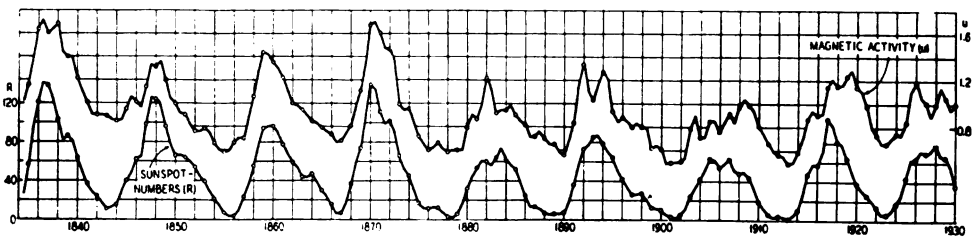


FIG. 23. CORRELATION BETWEEN SUNSPOT-NUMBERS AND MAGNETIC ACTIVITY, 1836 TO 1930 (AFTER DEPARTMENT OF TERRESTRIAL MAGNETISM).

RADIO ECHOES OF LONG DELAY

In 1927–28, Störmer and Hals announced the discovery[9] in Oslo, Norway, of radio echoes following short-wave signals (31.4 meters) emitted from a sending-station at Eindhoven in Holland. These delayed echoes have since been recognized by various other observers, although they seem to be very rarely detectable in European latitudes (35°–60° north). The delay of echoes recorded oscillographically from the ionized layers of the upper atmosphere is ordinarily from about 1 to 4 milliseconds. The delayed echoes, here considered, have been reported as following the generating-signal by an interval of from 1 to 30 seconds, a totally different order of magnitude. A great many of such delayed echoes were reported by J. B. Galle, at the island of Pulo Condore[10] in the tropics, during a French expedition to observe a solar eclipse which was total at that locality in May, 1929.

Two theories have been suggested to explain these extraordinary radio echoes. One was that the signal-ray penetrated the space between upper and lower ionized atmospheric layers, became greatly slowed down in group-velocity, oscillated to and fro between the layers, and finally returned to the ground after great delay. Pederson has shown that this theory is very unsatisfactory, for several reasons.

The other theory, put forward by Störmer, is that when cathode-rays

[8] E. O. Hulburt, "Tables of the Ionization of the Upper Atmosphere," *Phys. Rev.*, 39, 977–992, 1932.

[9] Carl Störmer, "Short-wave Echoes and the Aurora Borealis," *Nature*, 122, 681, 1928; also "Ueber die Probleme des Polarlichtes," Ergebnisse der kosmischen Physik, 1, 1–86, 1931.

[10] J. B. Galle, "Observations relatives à la radioélectricité et à la physique du globe faites à l'occasion de l'éclipse totale de soleil du 9 mai 1929 à Poulo Condore (Indo-Chine)," *Onde Électrique*, 9, 257–265, 1930.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

emitted by the Sun move towards the Earth there is, for a given stream-velocity, a certain radial distance from the Earth which they can not enter in a straight line, being deflected by the Earth's magnetic field. Under the influence of this field, the cathode-ray stream would carve out a toroidal hollow space, shaped like an apple, coaxial with the Earth's magnetic polar axis. The ionized walls of this toroidal space, at a radial distance of perhaps two millions of kilometers from the Earth, would be capable of acting as an ionized layer and of reflecting the waves back to the Earth, which is at the center of the tore. A short-wave radio signal capable of penetrating and emerging from the atmospheric ionized layer, would proceed as a straight ray to the toroidal surface, and when reflected back to the Earth, would make a journey of say 4,000,000 km, which would occupy about 13 seconds. Different velocities and masses of ionized streams, approaching the Earth, could set up toroidal reflectors at different distances.

Many more observations will be necessary to confirm or refute this ingenious theory of long-delayed echoes. Fig. 24, from one of Störmer's publications, indicates the incoming electronic streams descending to the Earth in curtain-like sheets around the Earth's magnetic poles, and forming, under favorable conditions, visible auroral clouds.

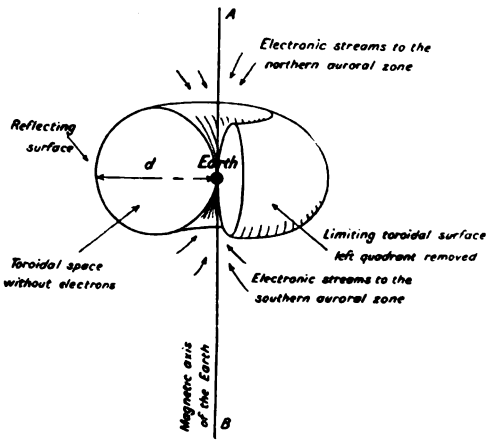


FIG. 24. DIAGRAMMATIC SKETCH OF THEORY FOR LONG-DELAYED ECHOES (AFTER STÖRMER).

CONCLUSIONS

It is evident that there are widespread cosmic influences which affect the magnetic field, auroras, the ionized air-layer and radio signals, at or near the surface of the Earth. Within the last few decades, radio has become available as a new research tool for exploring the upper air all round the world. The conjoint organization of a man directing a locomotive or an airship is a creative combination of much larger powers and radius of action than the same man unarmed. Since a properly equipped operator at a powerful radio station can invade the atmosphere up to say 200 km, the height of the ionized layers, all round the world, the conjoint organization of operator and radio becomes a spherical combination 40,000 km around, hollow, and 200 km thick. Moreover, if Störmer's theory of delayed echoes should be confirmed, the same operator, armed with radio waves, would become a conjoint organization with a toroidal sphere of influence having a radius of more than a million kilometers. In any event, careful study of radio wave-phenomena should enable the upper atmosphere to be explored to elevations that have heretofore been inaccessible to man.

In a certain sense, it is fortunate that the relations between radio wave-propagation and the various cosmic phenomena here considered, are so complex. If radio waves of all lengths were subject to one and only one simple law of transmission in passing through the Earth's atmosphere, the law might be easy to determine, but it could not be expected to elucidate the behavior of

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

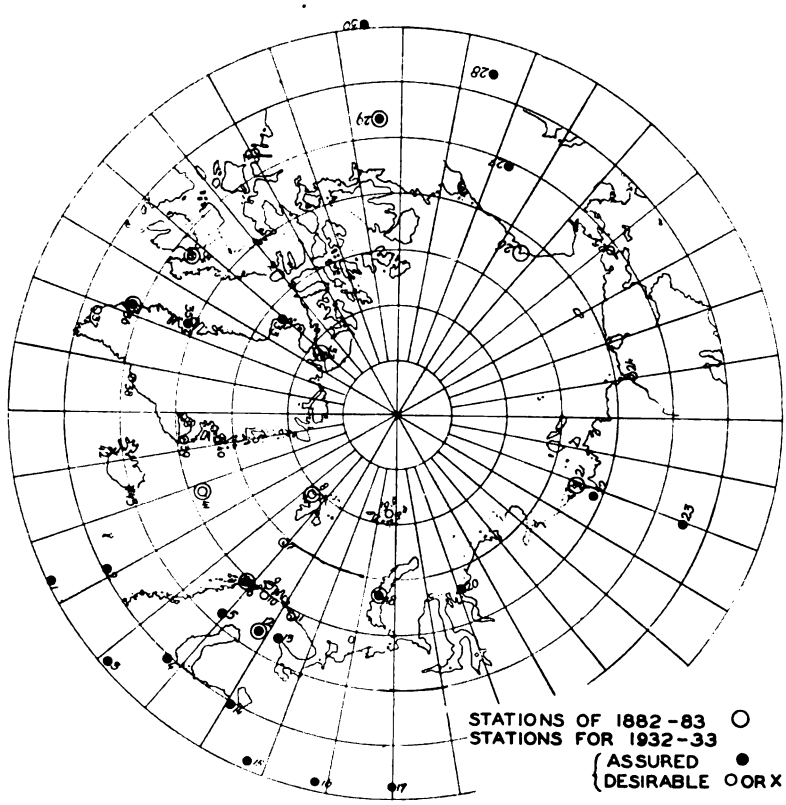


FIG. 25. DISTRIBUTION OF OBSERVING STATIONS IN THE POLAR REGIONS AS PROPOSED FOR THE INTERNATIONAL POLAR YEAR 1932–33 (AFTER INTERNATIONAL POLAR YEAR COMMISSION).

other cosmic influences. The transmission of radio waves is, however, dependent upon a number of conditions, including direction, wave-length, magnetic and electric phenomena, which make the problem more difficult, but promise much collateral information when it is finally solved.

Fig. 25 is a map of the northern polar hemisphere prepared by the International Polar Year Commission to show the magnetic stations that were occupied successfully by expeditions from more than twelve different nations in the "Polar Year" 1882–1883; also the stations that it is proposed to occupy during the forthcoming "Jubilee Polar Year," 1932–1933. The various nations will carry out a concerted program of meteorological, magnetic, electric and radio work, which should lead to the acquisition of much needed knowledge in all these directions. It can not be doubted that all such knowledge will lead to results of international importance and utility.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

TIDES IN THE ATMOSPHERE

By J. BARTELS

PROFESSOR OF METEOROLOGY, FORSTHOCHSCHULE OF EBERSWALDE, DOCENT IN GEOPHYSICS, BERLIN UNIVERSITY, RESEARCH ASSOCIATE, CARNEGIE INSTITUTION OF WASHINGTON

THE subject of this lecture is a part of the mechanics of the atmosphere, and I will therefore indicate at the outset how the atmospheric tides are fundamentally related to the main theme of these three lectures, namely, the magnetic field of the Earth and its atmosphere.

That part of the space to which we have direct access is a comparatively thin shell near the Earth's surface. A distance of 25 miles appears small to us if we travel it in horizontal direction, but a greater height than 25 miles has never been reached with any instrument. In this respect the higher regions of the Earth's atmosphere have been just as remote to us as the Moon or the Sun or the stars, and all our knowledge about them is based on the interpretation of various indirect observations. Such studies on the physics of the upper atmosphere have mainly a twofold interest: First, they reveal strong cosmic influences to which only these outermost regions are exposed, while the lower atmosphere in which we live is only indistinctly affected; and, second, the electrical state of these regions makes long-range radio communication possible.

Among the sources of information about the physical phenomena in these outermost layers, observations of terrestrial magnetism are outstanding. Nearly every variation in the Earth's magnetic force is caused by some electric phenomenon in the height, and most of the magnetic records of which Mr. Fleming showed typical examples two weeks ago are, so to say, messages from high altitudes which lend themselves to suitable interpretation. This holds for the irregular variations during magnetic storms and aurorae which Dr. Kennelly has discussed in his lecture, and particularly for the regular magnetic variations which follow the daily course of Sun and Moon. Indeed, as early as 1878, Balfour Stewart concluded from a discussion of these daily magnetic variations that they originate in the upper atmospheric layers, and that the air in these layers must conduct electricity much better than the air near the ground—a famous scientific hypothesis which was fully confirmed, over 20 years later, after the invention of wireless communication. Balfour Stewart also pointed out that the ultimate cause of the regular daily magnetic variations was atmospheric oscillations of the character of tidal motions. If, for instance, the moon would not perform, day by day, on the Earth's atmosphere that large-scale experiment that results in the lunar atmospheric tide, then we should not observe a certain kind of delicate magnetic variations and should lose, with them, a unique opportunity to study significant changes in the electrical state of the upper atmosphere. The outcome of these systematic experiments of Sun and Moon have been continually watched for many years by a number of magnetic observatories under varying conditions of season, number of sunspots, magnetic activity, distance and relative position of the Moon, and so on. The re-

[1] The third in a series of three lectures concerning the magnetic field of the Earth and its atmosphere delivered at the Carnegie Institution of Washington, March 22, 1932.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero

Digitized by Google

Original from UNIVERSITY OF MINNESOTA

sults of the discussion have already been of great interest and will be amplified by the reduction of the data from the two magnetic observatories of this institution, which, because of their geographical locations, are specially favorable for research of this kind. While the detailed theory is fairly complicated and will not be outlined here, you will see now why the tides of the atmosphere have lately been studied more by the magneticians, who use them for the interpretation of their magnetic data, than by the meteorologists, who in fact find the tides rather tedious and of no use for explaining or forecasting the weather.

Let us now speak of the tides themselves. We think naturally at once of the regular rise and fall of the water on the seashore, twice daily, and of the corresponding tidal water-currents. These are familiar effects of the tidal forces which Moon and Sun exert on our planet. We can describe these forces as tending to stretch the Earth in the direction of the line drawn between Earth and Moon, or Earth and Sun, and while the solid Earth yields only partly to these stresses, the sea-water is fairly free to follow them. The influence of the Moon is about twice as great as that of the Sun, and since the Moon attains every day her greatest altitude in the sky about 50 minutes later than on the preceding day, the times of high water on the seacoast are about as much retarded from day to day.

Air is about a thousand times lighter than water, but it has a certain mass and is therefore subject to gravitational attraction—we can say fortunately, because otherwise the air would long ago have diffused into space, and the Earth would be as barren as the Moon whose mass is too small to hold an atmosphere. Just as the air is attracted to the Earth, it must also, like the sea-water, follow the tidal forces, because they have their origin in gravitation. But how can we hope to verify this theoretical conclusion, in other words, how can we observe these tidal effects in the air? There is no coast from which we could watch the tides. One could think of detecting the atmospheric tides in the wind-changes which would be equivalent to the tidal currents in the ocean, but the wind is mostly locally distributed by varying friction since we live at the bottom of the air-ocean. At last we find in the barometer a suitable instrument. Under ordinary meteorological circumstances, namely, the weight of the mercury-column in a barometer is equal to the weight of an air-column of the same cross-section (Fig. 1). So, except during heavy storms or hurricanes, the pressure, as read on the barometer, is a measure of the mass of the air over the station; if we apply the usual barometer-corrections, we can indicate the pressure, the weight of the mercury-column, simply by the length of that column expressed in inches (about 30) or, more conveniently for our purposes, in millimeters (about 760).

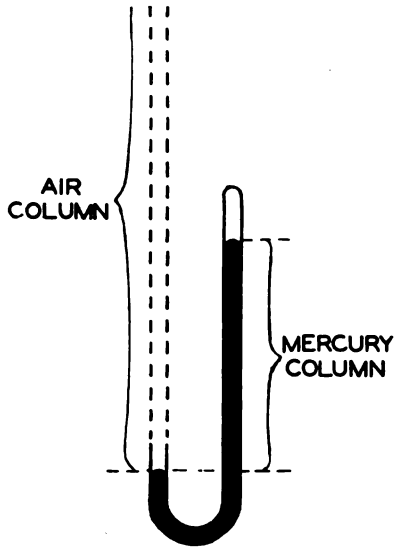


FIG. 1. BAROMETER WEIGHS ATMOSPHERE.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

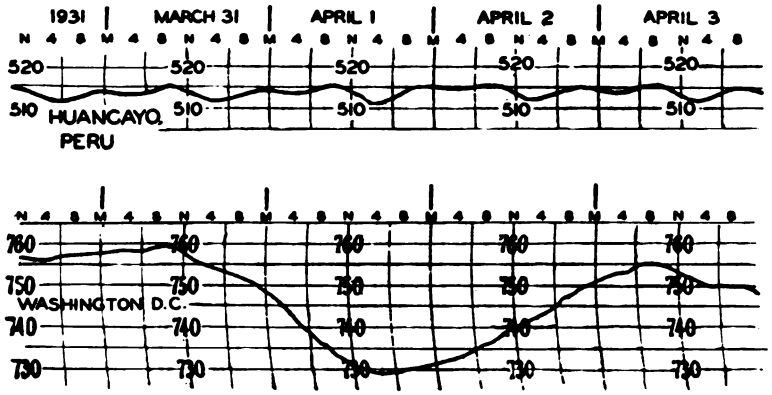


FIG. 2. BAROGRAPH CURVES AT HUANCAYO, PERU, AND WASHINGTON, D. C.

Continuous records of barometric pressure are given by the barographs, and in these curves we ought to look for tidal effects. Fig. 2 shows typical original records for the same day for two stations, one in the tropics, one in temperate latitudes. The contrast is obvious: At Washington we find the long waves connected with the weather changes during the passage of areas of high and low pressure; at first sight no systematic daily influence, no diurnal variation at all can be discerned. At Huancayo, however, we see day by day a regular double wave with the main maximum and minimum at 10 A. M. and 4 P. M., and secondary maximum and minimum at 10 P. M. and 4 A. M. (The low mean value of the pressure, 512 mm, at Huancayo is due to the altitude of our observatory, 11,000 feet above sea-level.) This regular phenomenon has been known more than 250 years and is observed everywhere in the tropics on land or sea, that is, on nearly half of the Earth's surface. The regular rise and fall of the pressure in the tropics is practically independent of the weather, only hurricanes can interrupt it. It also changes little with season, as the average diurnal curves for the months show for Key West in Florida (Fig. 3).

We are reminded of tides, because there is twice daily high pressure, and twice low pressure, but these maxima and minima occur every day at the same local time, at 10 and at 4 o'clock, and are not retarded from day to day as the ocean-tides. So they can not be related to the Moon, but must be produced by the Sun. However, they can not be simply the tides produced by the Sun, because we should then expect the maxima about noon and midnight or somewhat later, but not two hours *earlier* at 10 o'clock. Another possible cause might be the Sun's radiation, which results in the heating of the air in daytime and

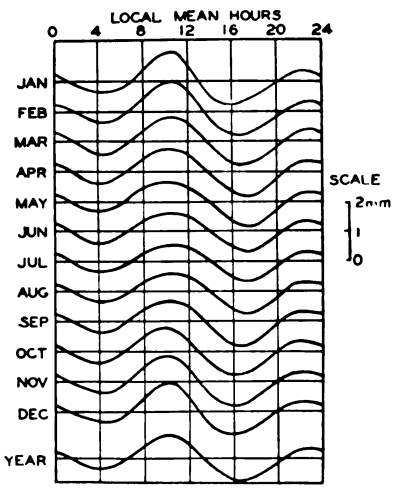


FIG. 3. DIURNAL VARIATION OF PRESSURE, KEY WEST, FLORIDA (AFTER HUMPHREYS).

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

the cooling at night, but this is essentially a single wave, per day, with one maximum of the temperature in the afternoon, and one minimum in the morning before sunrise, and it is hard to see how such a single wave could produce a double wave in pressure.

In order to approach this famous question, we shall analyze the barograph-records more closely and shall start with reading from these barograph-curves the values of pressure hour by hour (Fig. 4). These tabulations are, so to say, our raw material. From all the hourly values in a certain month we can form the average of all the observations taken at midnight, then those at 1 A. M., etc. In this way we derive an average variation of pressure throughout the day, the diurnal variation. These are shown in Fig. 5 for Washington, D. C., in an average for the months with the shortest days (December-January) and in an average for the months with the longest days (June–July); 14 years of observations were used. Both curves show high pressure in the forenoon, low pressure in the afternoon; the variation in the night-hours is much smaller than in the daylight-hours.

By a simple mathematical process we can represent these diurnal curves as the sum, as the superposition, of a number of curves of very simple form, so-called sine-waves. All sine-waves have similar forms. They are mainly distin-

DATE	LOCAL MEAN HOURS 0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	700 mm + ···														
16	53.8	53.9	54.0	53.9	54.0	53.8	53.9	53.9	53.8	53.4	53.4	53.2	52.9	53.0
17	52.6	52.4	52.1	52.0	51.8	51.8	51.7	51.8	51.8	51.8	51.0	51.4	51.1	50.9
18	52.1	51.9	51.9	51.7	51.7	51.7	51.6	51.6	51.4	51.0	51.0	50.5	50.0	49.8
19	51.5	51.7	52.1	52.5	52.7	53.0	53.1	53.2	53.2	53.2	53.1	52.6	52.2	51.6
20	47.7	47.0	46.7	46.8	46.8	46.5	46.5	46.7	47.2	47.5	47.7	47.8	47.6	47.7
21	46.7	46.5	46.4	46.6	46.4	47.0	47.0	47.2	47.2	47.1	47.3	47.6	47.3	47.1
22	47.8	47.8	47.4	47.5	47.7	47.9	48.3	48.7	48.9	49.3	49.6	49.8	50.1	50.2
23	54.9	55.2	55.5	56.0	56.6	57.2	57.8	58.3	58.7	59.0	59.2	59.3	59.4	59.6
24	61.1	60.9	60.8	60.8	60.7	60.7	60.8	60.8	60.7	60.4	60.0	59.6	59.2	59.1
25	54.7	54.3	53.9	53.4	53.2	52.8	52.6	52.5	52.3	51.8	51.6	51.7	51.7	51.7
26	50.9	50.7	50.6	50.5	50.4	50.6	50.4	50.8	50.9	51.0	51.0	51.0	50.9	50.8
27	52.1	52.2	52.1	52.2	52.4	52.6	52.9	53.2	53.4	53.6	53.2	52.9	52.3	52.1
28	51.8	52.0	52.2	52.4	52.7	53.1	53.3	53.8	54.5	55.1	55.5	55.9	56.1	56.3
29	58.4	58.4	58.5	58.6	58.7	58.9	59.0	59.2	59.2	59.1	58.8	58.5	58.1	57.6
30	56.1	54.7	54.4	53.9	53.6	53.2	52.9	52.7	52.5	52.4	52.4	52.3	51.9	51.8
MEAN	53.8	53.73	53.69	53.59	53.58	53.70	53.77	53.89	53.99	54.02	53.97	53.86	53.75	53.64

FIG. 4. SPECIMEN OF HOURLY TABULATIONS OF AIR-PRESSURE, SEPTEMBER 16–30, 1930, AT POTSDAM, GERMANY.

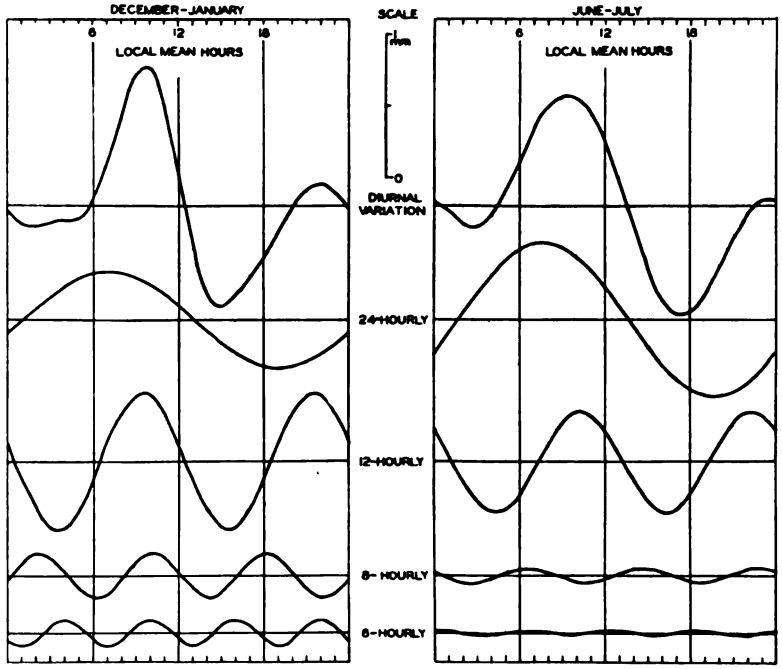


FIG. 5. HARMONIC ANALYSIS OF DIURNAL VARIATION OF PRESSURE AT WASHINGTON, D. C.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

guished by their periods, that is, the times in which they complete a full wave or cycle (here 24, 12, 8 and 6 hours, respectively); and sine-waves of the same period are characterized by their amplitude, that is, their greatest deviation from the mean line, and by the time of occurrence of their maximum. The decomposition of a diurnal variation into sine-waves with the periods of a full day, half a day, one third, one fourth of a day, etc., is called harmonic analysis; it would be possible to find also sine-waves of smaller periods of one fifth of a day, etc., but that is in general unnecessary, since the superposition of the first four sine-waves already approximates the diurnal variation sufficiently well.

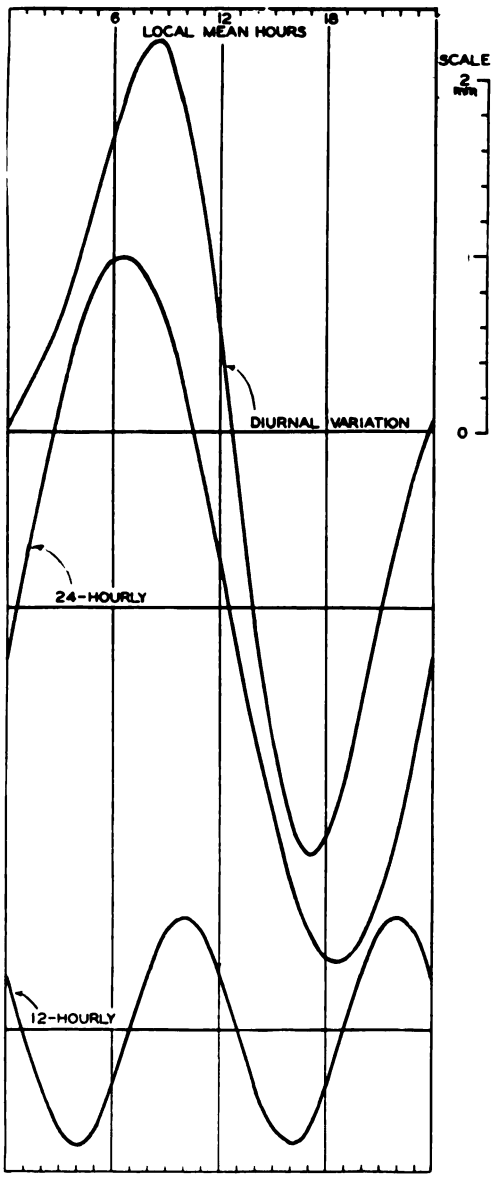


FIG. 6. HARMONIC ANALYSIS OF PRESSURE IN SUMMER, DEATH VALLEY, CALIFORNIA.

The process of harmonic analysis is entirely formal, mathematical, and can be applied to any curve. If, for instance, we should find pleasure in counting the number of people crossing 12th Street on F Street per hour, we might also derive a diurnal variation, this curve could also be subjected to harmonic analysis, but this would be nothing but a mathematical amusement. The reason why we apply harmonic analysis to pressure observations is mainly that theory leads us to expect sine-waves in the oscillations of the atmosphere, just as sine-waves appear in every other physical phenomenon of oscillation. Such physical phenomena are abundant in number; in fact, when we listen to a radio program, our ear combines millions of different acoustic sine-waves. These are transmitted by a still greater number of electromagnetic sine-waves which pervade the space in such a multitude that we can only be glad that they do not act directly on any of our senses and turn us into nervous wrecks.

We may at once realize the advantage of harmonic analysis when we notice that the twelve-hourly sine-wave in pressure at Washington is nearly the same in winter and summer, with maxima at 10 o'clock in the morning and evening, minima at 4 o'clock in the morning and afternoon. So we have found again the tropical double wave, which is only hidden in the diurnal variation by other waves. The 24-hourly wave has larger amplitudes in summer than in winter, with the maximum about

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

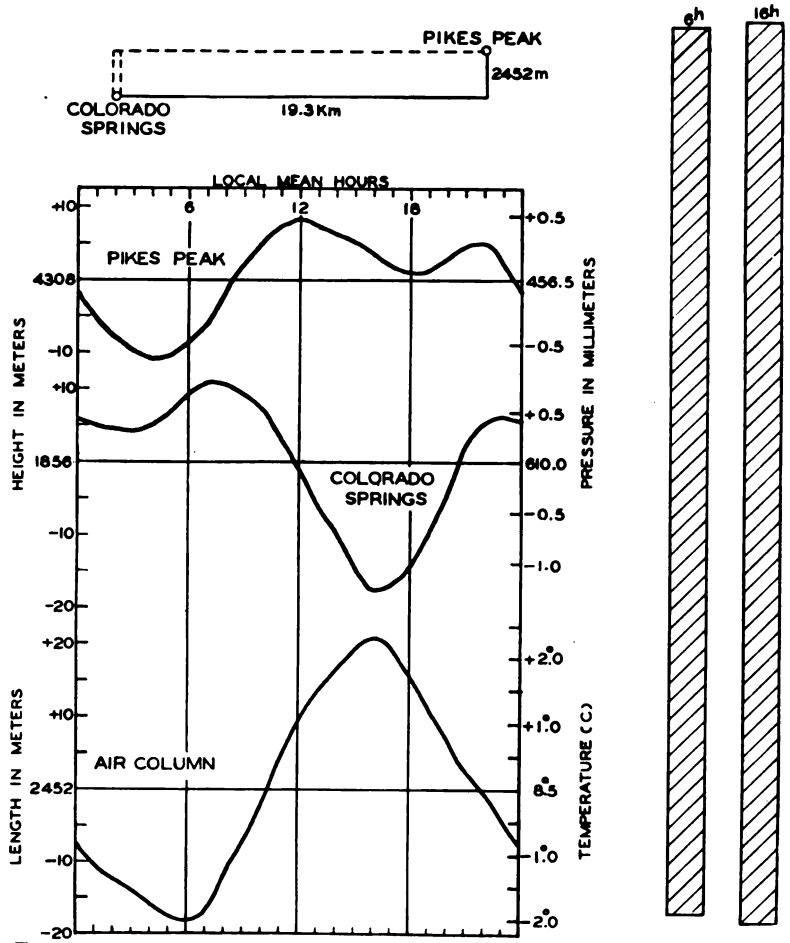


FIG. 7. TEMPERATURE-VARIATION IN THE FREE ATMOSPHERE DERIVED FROM BAROMETRIC OBSERVATIONS.

6 o'clock in the morning. The 8-hourly wave is interesting because in winter it has its first maximum about 2 o'clock, but in summer its first minimum at the same time; the crests and troughs of the 8-hourly wave have reversed their places from winter to summer.

Some examples will show the great differences in the diurnal variation of pressure at different stations. The diurnal variation is especially pronounced at the bottom of valleys; at Death Valley in California, the pressure in summer at 5 P. M. is 4.6 mm smaller than at 8 A. M. (Fig. 6). Harmonic analysis finds the 24-hourly wave responsible, while the 12-hourly wave is again quite normal as to amplitude and time of maximum.

Next we consider the summer conditions on top of a mountain (Pike's Peak) and at a base-station (Colorado Springs); the relative position of the two stations is indicated in the small vertical section at the top of Fig. 7. The diurnal variations of pressure, as shown in the two upper curves, look very different.

We can account for this difference in the following way: Consider a barometer at a fixed height. At a certain time it may indicate a pressure of 750 mm. We know that pressure increases downward and decreases upward in the

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

atmosphere. If, therefore, the reading of the barometer after some time rises to 751 mm, we can find vertically above the station a level where the pressure is 750 mm, and if our fixed barometer falls below 750 mm, we can find the pressure 750 mm at some lower level. In other words, every rise and fall in the reading of a barometer can be expressed as the rise or fall of the level where the pressure has a given constant value.

The two upper curves in Fig. 7 can therefore be interpreted in two ways—either using the scales on the right, as diurnal variations of pressure in the fixed heights 4,308 m and 1,856 m above sea-level, or, using the scales on the left, as the diurnal rise and fall of the levels of constant pressure 456.5 mm and 610.0 mm. These levels of constant pressure are so nearly horizontal that the data for Pike's Peak can be considered as a good approximation for the conditions in the free atmosphere over Colorado Springs. The two curves represent, therefore, the vertical movements of the upper and lower levels of a certain vertical air-column in the course of a day. Remembering that the barometer weighs the atmosphere, we see that the total mass M of air above the bottom level of the column must be constant (corresponding to the constant pressure 610.0 mm), and also the total mass m of air above the top level of the column (corresponding to the constant pressure 456.5 mm); consequently, the mass of the air $(M - m)$ in the column also must be constant. The third curve in Fig. 7, which is the difference of the two upper curves, represents therefore the changes in the length of this column throughout the day. It is, on the average, 2,452 m long, but at 6 A. M. it is 18.0 m shorter, and at 4 P. M. it is 20.7 m longer, as shown to scale in the two columns sketched in the right-hand part of the diagram. These contractions and dilatations of the column can only be interpreted as corresponding changes in the mean temperature of the air in the column because, as we have seen, the column contains always the same mass of air. This is done by the scale at the right of the lower curve; the column which, on the average, has the temperature 8.°5 C. is 2.°0 C. cooler at 6 A. M., and 2.°3 C. warmer at 4 P. M. We have thus obtained from barograph-readings an estimate for the variation of the temperature in the free air between the levels of the two stations on top and at the foot of Pike's Peak—and a very reliable estimate it is, which could not be as readily deduced from direct balloon-observations of temperature.

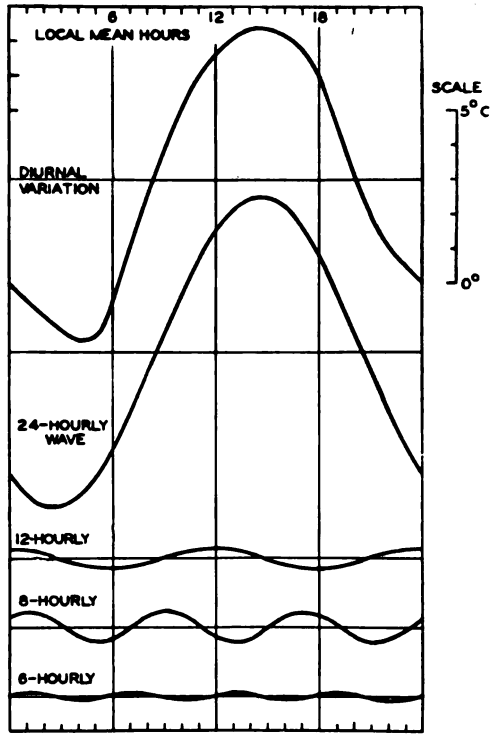


FIG. 8. HARMONIC ANALYSIS OF AIR-TEMPERATURE IN JUNE AT POTSDAM, GERMANY.

I have treated this simple calculation at some length here, because its plausible result incidentally supports our rule on which the calculation was based, namely,

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

that the barometer weighs the atmosphere. This has sometimes not been realized, and just recently (in connection with the absorption of the penetrating radiation by the atmosphere) the question has been revived in its simplest form. Consider two balloons full of air, one hermetically closed, the other with an opening. If these balloons are heated, the pressure in the closed balloon will rise and the rubber will burst eventually, but in the open balloon the pressure remains practically the same since the air can expand freely and flow out. The conditions of the atmosphere at sunrise have been compared to those in the closed balloon; it has been said that the Earth is so rapidly heated in the morning that the air (partially confined, because of its viscosity and inertia), can not expand fast enough, and the pressure rises simply because of the heating. This was offered as an explanation of the morning maximum of pressure. This opinion may, however, be proved to be wrong; the atmosphere corresponds to the air in the open balloon, because it can expand vertically fast enough and can adjust itself to the diurnal variation of temperature. Diurnal variations of pressure are really only due to corresponding changes in the weight of the atmosphere above the station, and such changes in the weight can only occur through horizontal movements of air, that is, through winds. These winds—land- and sea-breeze, mountain- and valley-breeze—may be too weak to be noticeable every day, but the systematic shift of air-masses is sufficient to be recorded by the barometer and to be brought forth in the average of many days. Since these winds are mainly local in character and depend mostly on the differential heating of different parts of the Earth's surface—land and sea, for instance—they will have a diurnal variation which is similar to that of their cause, the temperature of the air; that is, mainly a 24-hourly wave as shown in Fig. 8. This explains why the local differences in the diurnal variations of pressure are confined to the 24-hourly sine-wave, but scarcely affect the 12-hourly sine-wave.

This distinction is again brought out in Fig. 9; both on Pike's Peak and at Colorado Springs the 12-hourly pres-

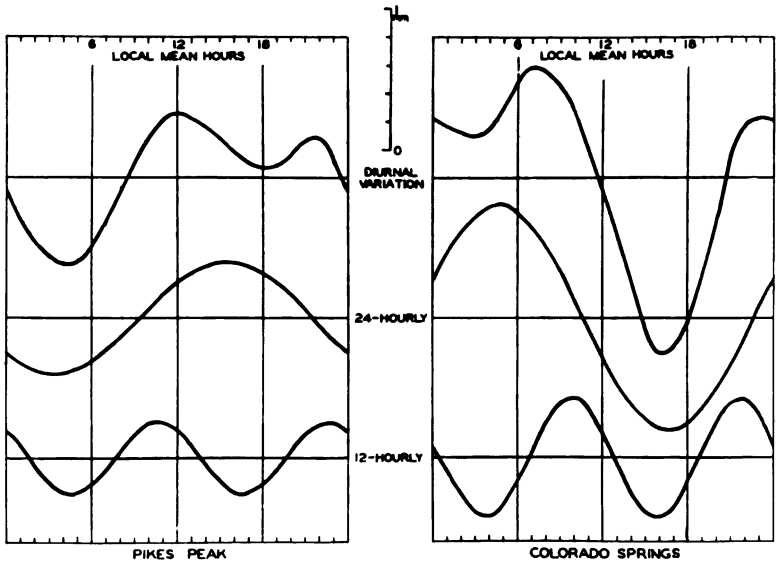


FIG. 9. HARMONIC ANALYSIS OF PRESSURE IN SUMMER.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

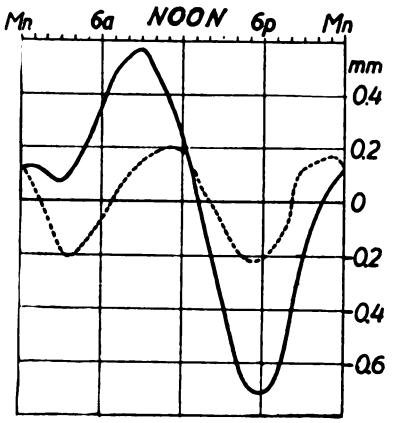


FIG. 10. DIURNAL VARIATION OF PRESSURE ON CLEAR (FULL LINE) AND CLOUDY DAYS IN JUNE AT POTSDAM, GERMANY (AFTER WIEN-HARMS).

sure-wave has its maximum near 10 o'clock in the morning and in the evening, while the 24-hour waves on the top and at the foot of the mountain are exactly reversed.

The mainly local character of the 24-hourly wave of pressure as against the universal character of the 12-hourly wave can finally be ascertained in the following way: On cloudy days, the diurnal variation of temperature is small as compared with clear days. Consequently, the shift of air between land and sea and the accompanying winds and variations of pressure will also be smaller on cloudy days. This is shown in Fig. 10; on clear days, there is only one maximum and one minimum in pressure, but, on overcast days, all local effects are diminished, and only the world-wide 12-hourly wave of pressure persists. Fig. 10, simple as it looks, is the only reliable curve of its kind which has ever been derived, because the numerous other attempts have been badly spoiled by a curious systematic curvature-effect which is connected with the selection of clear and cloudy days and has always been overlooked.

It would be tedious to show the universal character of the 12-hourly wave of pressure by more curves of the same kind. A more convenient way of representing sine-waves is explained in Fig. 11. It shows the 12-hourly wave of pressure at Washington, D. C., in winter, above in the usual way, below in the so-called harmonic dial. This is nothing but a graph of the dial of an alarm-clock, in which the hand points towards the time of maximum, while the amplitude of the wave is indicated by the hand. This simple graph replaces the curve in every way, because the form of a 12-hourly sine-wave is completely given if we know its amplitude and time

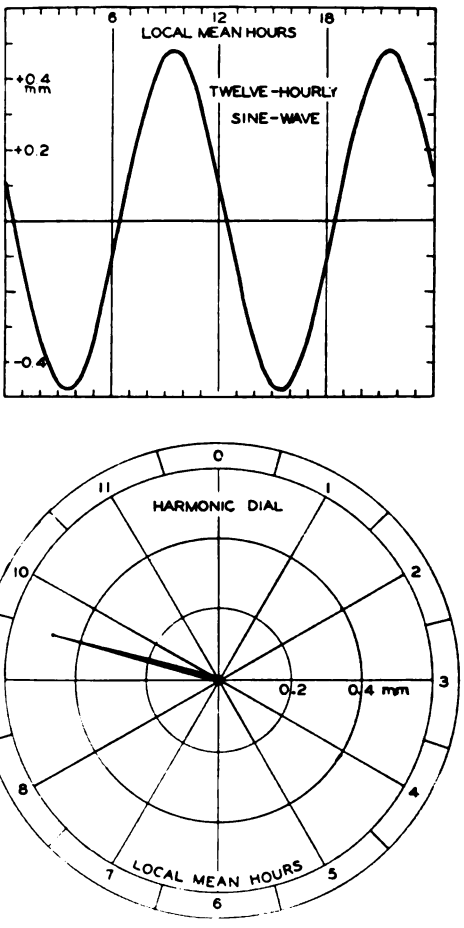


FIG. 11. ATMOSPHERIC PRESSURE FOR DECEMBER AND JANUARY, WASHINGTON, D. C.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

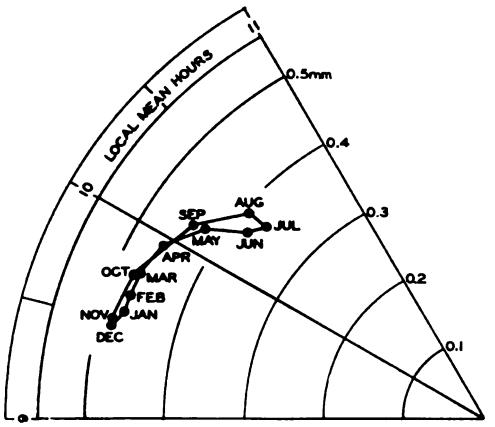


FIG. 12. HARMONIC DIAL FOR TWELVE-HOURLY WAVES OF PRESSURE, WASHINGTON, D. C.

of maximum. The harmonic dial can be further simplified by indicating the hand only by its end-point; it has then the advantage that more than one wave can be shown on the same dial. We can further omit unnecessary parts of the dial. This has been done in Fig. 12, which shows the 12-hourly waves of pressure at Washington, D. C., for every month. Only the end-points of the hands for each month are drawn and counted in succession; throughout the year, the maximum occurs between 9^h 30^m and 10^h 30^m, and the amplitude remains about 0.4 mm.

In the chart of North America (Fig. 13), harmonic dials are imagined with their center at all those meteorological stations for which the 12-hourly (or semi-diurnal) wave of pressure, in the average for the whole year, has been computed from actual observations; only the hands of the dial are shown. The amplitude diminishes from the tropical regions towards the north (from 0.9 mm in the West Indies to 0.3 mm at Cleveland and Chicago), but the maxima occur everywhere with astonishing regularity about 10 o'clock local time. Using the conception of the harmonic dial as an alarm-clock which rings at the time of the maxima, we should hear the alarm 2 hours before noon and 2 hours before midnight, progressing from east to west across the continent with a speed of about 800 miles per hour—much faster than any cyclone.

In the schematic world-chart (Fig. 14), this progressive 12-hourly wave is represented by isobars, that is, lines of

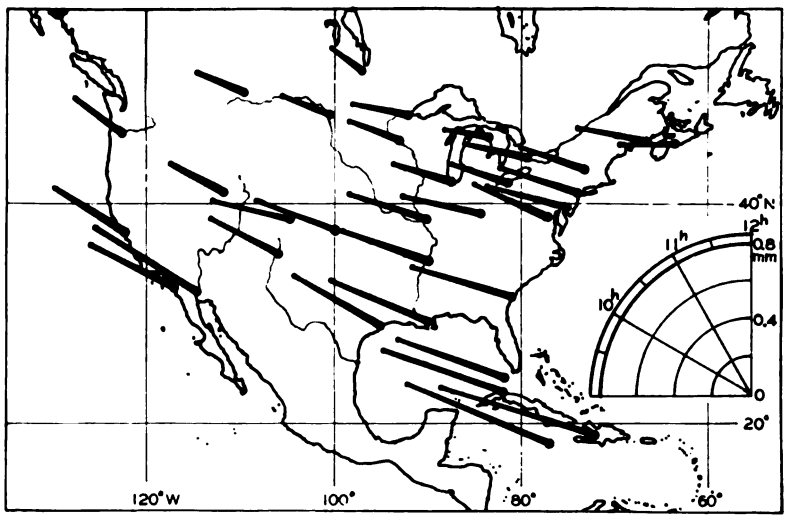


FIG. 13. SEMI-DIURNAL SOLAR WAVES OF ATMOSPHERIC PRESSURE IN NORTH AMERICA: SCHEME FOR HARMONIC DIAL SHOWN BY INSET.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

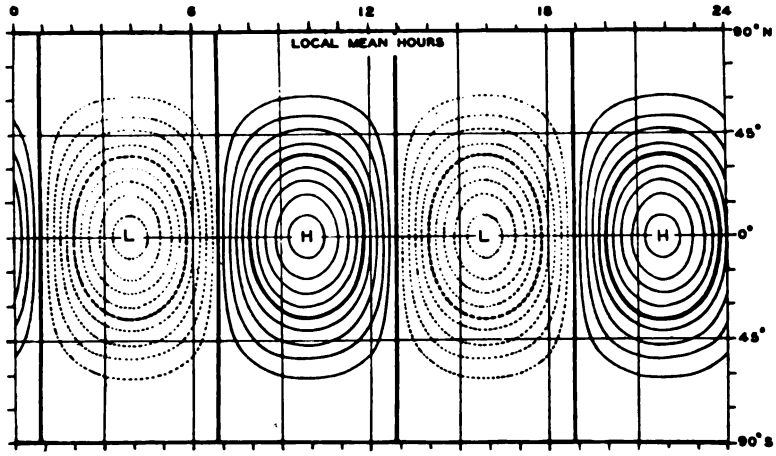


FIG. 14. WORLD CHART OF PROGRESSIVE TWELVE-HOURLY WAVE—ISOBARS 0.1 MM DISTANT (FROM NATURWISSENSCHAFTEN).

equal pressure, drawn 0.1 mm apart; as in a weather-chart, we recognize two areas of high pressure (H), centered at the equatorial points where the time is $9^h\ 50^m$ in the morning and evening, and two areas of low pressure (L) at $3^h\ 50^m$. This double wave travels with the Sun from east to west. The chart shows how the amplitudes decrease towards the poles, from nearly 1.0 mm at the equator to 0.1 mm in 60° latitude.

In the polar caps, the 12-hourly wave is very small and seems irregular. In the harmonic dial, on the left in Fig. 15, the values of the 12-hourly pressure-wave for the polar stations north of 70° north are marked by small circles, and those for polar stations south of 65° south by small crosses. The maxima are scattered all over the dial, instead of occurring about 10 o'clock as we have seen for non-polar stations. This irregularity is, however, only apparent and turns into a striking regularity if we use, not the dial of local time, but one of universal time, for instance, Greenwich mean time. This transformation is done in the right-hand dial of Fig. 15; as though by magic, all the points arrange themselves about $11.^h5$ Greenwich time. Somewhat idealizing we can say that the alarm-clocks ring in both polar caps simultaneously. The amplitude is about 0.1 mm at the poles.

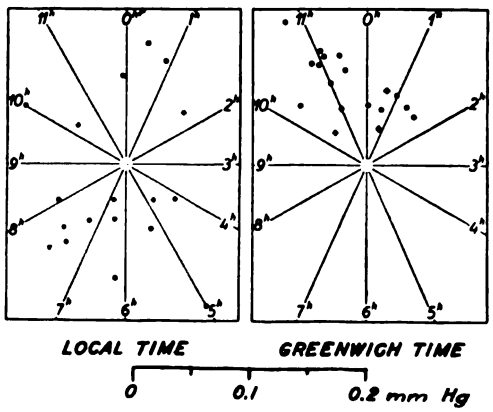


FIG. 15. HARMONIC DIAL OF SEMI-DIURNAL VARIATION OF PRESSURE FOR POLAR STATIONS NORTH OF 70° N. (CIRCLES) AND SOUTH OF 65° S. (CROSSES) (AFTER WIEN-HARMS).

Mathematical analysis can detect this polar wave also at a greater distance from the poles, where it is of course combined with the main progressive wave. An isobar chart of the polar region (Fig. 16) shows zones of high and low pressure; this wave is therefore called zonal. It is stationary, that is, the nodes (in about 35° latitude) remain fixed. The chart shows the conditions at $11^h.5$ Greenwich time (the time of maximum in the polar zones); 3 hours later there

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

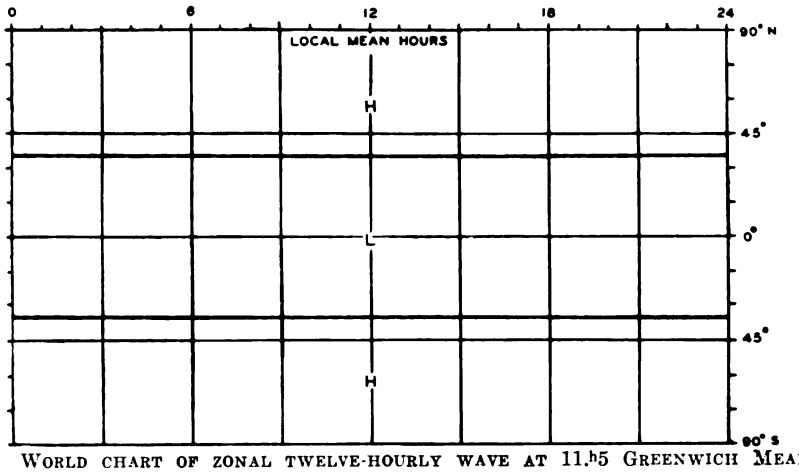


FIG. 16. WORLD CHART OF ZONAL TWELVE-HOURLY WAVE AT 11.h5 GREENWICH MEAN TIME (FROM NATURWISSENSCHAFTEN).

would be no pressure-differences, 6 hours later the polar caps would have low pressure and the equatorial zone high pressure, and 12 hours later the distribution of pressure would be again the same as shown in the figure.

An 8-hourly wave of pressure had long been overlooked, because the theory of the gravitational tides does not predict such a wave. It exists, however, and not merely as a mathematical fiction, but as a separate progressive wave of a strange symmetry. Fig. 17 shows, for two stations in the northern hemisphere, the 8-hourly waves for each month in harmonic dials, which, for economy, have been cut down to the form of wrist-watches, and which show only the times of the first maxima in the day, because the two others occur exactly 8 and 16 hours later. The amplitudes are small, of the order of 0.15 mm, and a bit larger at Washington than at Potsdam, but otherwise the dials for both stations show the same features. In the winter months, the first maximum occurs shortly after 2 o'clock in the morning, the first minimum, therefore, at 6 o'clock. In the summer months, the wave is exactly reversed: We read from the dial that the first maximum of pressure occurs shortly after 6 o'clock in the morning, just the time when the first minimum occurs in winter! We find this reversal from summer to winter again in the 8-hourly wave of temperature (Fig. 18); this indicates a relation of cause and effect between the 8-hourly waves of temperature and pressure which is confirmed by theory.

The world chart for the 8-hourly wave of pressure (Fig. 19) is drawn for December, that is, winter in the northern,

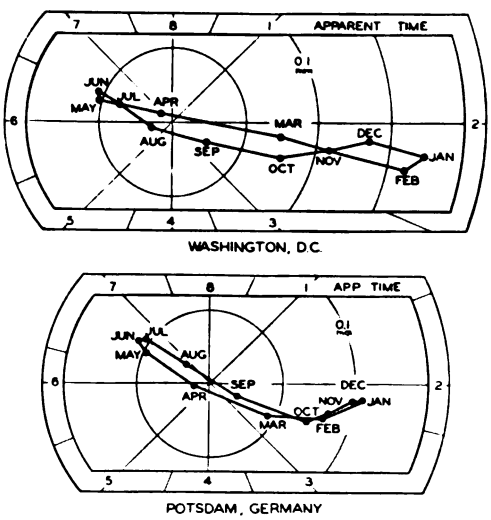


FIG. 17. HARMONIC DIALS FOR EIGHT-HOURLY WAVES OF PRESSURE, WASHINGTON, D. C., AND POTSDAM, GERMANY.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

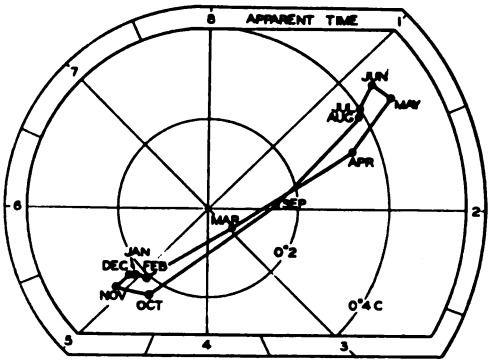


FIG. 18. HARMONIC DIAL FOR EIGHT-HOURLY WAVE OF TEMPERATURE, POTSDAM, GERMANY.

and summer in the southern hemisphere. The areas of high and low pressure are therefore opposite on both sides of the Earth's equator. The amplitude is highest, about 0.15 mm, in 30° latitude. The chart for June would look similar, but the letters H and L would exchange their places. (This world-chart does not show that the amplitude of the 8-hourly pressure-wave is smaller in summer than in winter; it contains only the relevant part, corresponding to the anti-symmetric spherical harmonic P_4^3. In other words, the monthly means of the waves are not reckoned from the origin of the dial in Fig. 17, but from the center of gravity of the twelve monthly dots, that is, the average for the whole year.)

The horizontal winds near the Earth's surface which accompany the 12- and 8-hourly pressure-waves are shown in the schematic charts in Fig. 20. The isobars in these charts are copies of characteristic parts of the diagrams Figs. 14 and 19. It is interesting to note how the wave-motion progresses towards the west, since all the wind arrows converge to the points where the high pressure will have moved after a quarter of the period (3 or 2 hours). These periodic winds are weak, less than about 2 feet per second, or about one mile per hour. If there were no other winds, an air-particle would describe regular ellipses of about 2 miles extent for the 12-hourly wave, and one third of a mile for the 8-hourly. Similar air-movements in the high layers of the atmosphere are the cause of the magnetic variations which were mentioned at the beginning.

The systematic harmonic analysis has, as we have seen, revealed regular world-wide oscillations of the atmosphere in the solar diurnal-variations of pressure. The search for corresponding influences of the Moon was first successful for tropical stations, but met great difficul-

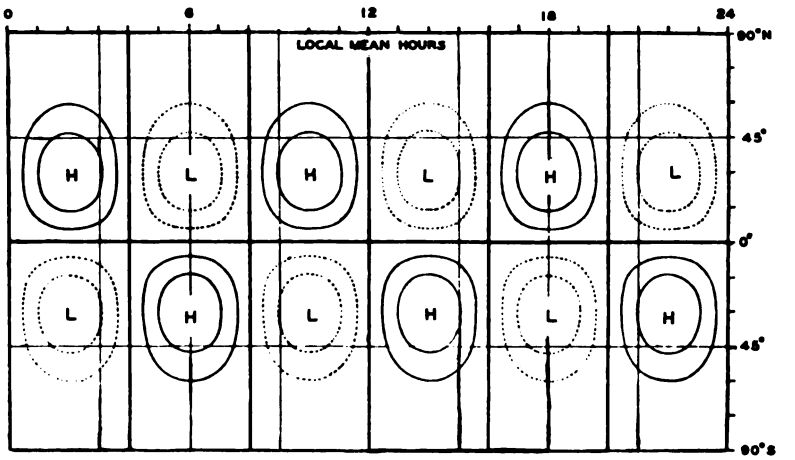


FIG. 19. WORLD CHART OF PROGRESSIVE EIGHT-HOURLY WAVE FOR DECEMBER—ISOBARS 0.5 MM DISTANT (FROM NATURWISSENSCHAFTEN).

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

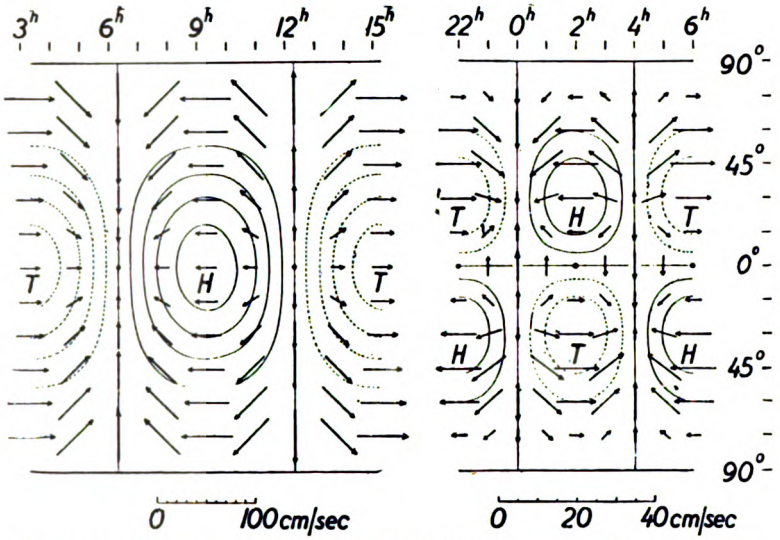


FIG. 20. CHART SHOWING HORIZONTAL AIR-MOVEMENTS IN THE PROGRESSIVE TWELVE-HOURLY (LEFT) AND EIGHT-HOURLY DIURNAL WAVES OF PRESSURE (AFTER WIEN-HARMS).

ties for stations in higher latitudes because of the great unperiodic variations of pressure which are connected with the weather changes. Laplace used nearly 5,000 barometric observations taken through eight years at Brest, and Airy used 160,000 hourly observations taken through twenty years at Greenwich, but both analyses failed, and satisfactory results have been obtained only in recent years, mostly by S. Chapman.

In principle, the calculation of a lunar variation is the same as that of a solar variation. A *solar* day is reckoned from midnight to midnight or, as the astronomers say, from one lower transit of the Sun to the next; the upper transit is noon. In the same way we may introduce a *lunar* day from one lower transit of the Moon to the next, an interval about 50 minutes longer than a solar day. The lunar day can again be divided into 24 lunar hours. Starting from our raw material, the hourly values of pressure for a number of years, we combine all pressure-observations for the first lunar hour, for the second lunar hour, etc. The result derived from 66 years of observations at Potsdam and Hamburg are

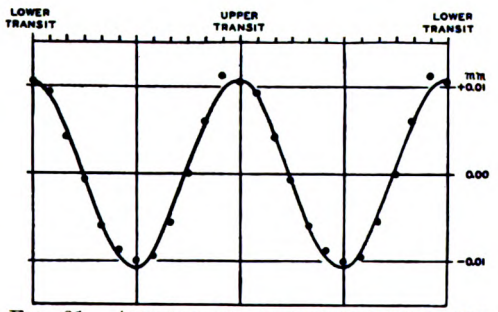


FIG. 21. AVERAGE LUNAR PRESSURE-WAVE FOR POTSDAM AND HAMBURG, GERMANY (FROM NATURWISSENSCHAFTEN).

represented by dots in Fig. 21, which fit into a beautiful sine-wave of 12 lunar hours period, a lunar semi-diurnal wave, with high pressure near the lower and upper transit of the Moon, just as tidal theory predicts. Why it was so difficult to obtain this curve is explained by the extremely small amplitude, 0.01 millimeter; the pressure is only 0.02 mm higher, when the Moon stands highest in the sky or lowest below the horizon than when the Moon is just rising or setting in the horizon. The curve, as it appears in Fig. 21, shows the actual lunar rise and fall of the mercury column of

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

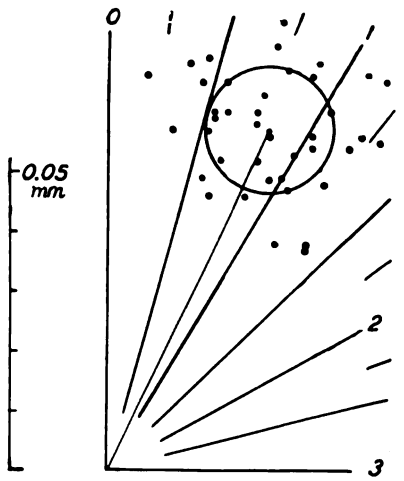


FIG. 22. SEMI-DIURNAL WAVE IN PRESSURE FOR LUNAR HOURS—BATAVIA, 1866–1905 (AFTER WIEN-HARMS).

the barometer, about 1,000 times enlarged. An ordinary barograph-curve of 40 mm width, such as that shown for Washington in Fig. 2, would, on the same scale, be about 120 feet high, and even the trace of the recording pen would appear about 8 inches wide. This minute lunar wave is, so to say, drowned in the large irregular waves of the ordinary high- and low-pressure areas, and its detection is the triumph of certain statistical methods which had to be developed for the discovery of such hidden periodicities. This improvement of the analytical methods which was necessary for the computation of the lunar tides in atmospheric pressure has sharpened the tools with which we may test the great number of other cycles and periods which have been claimed in geophysical and cosmical phenomena.

The computation of the lunar atmospheric tide is also a typical geophysical problem in another direction. The raw material from which the computation starts consists of readings of the barograms to 0.1 mm such as 759.1 mm; the result is a curve which is accurate to 0.001 mm. It looks as though a higher precision of the original observations—to 0.01 mm, for instance, which is quite feasible—might be helpful. But this

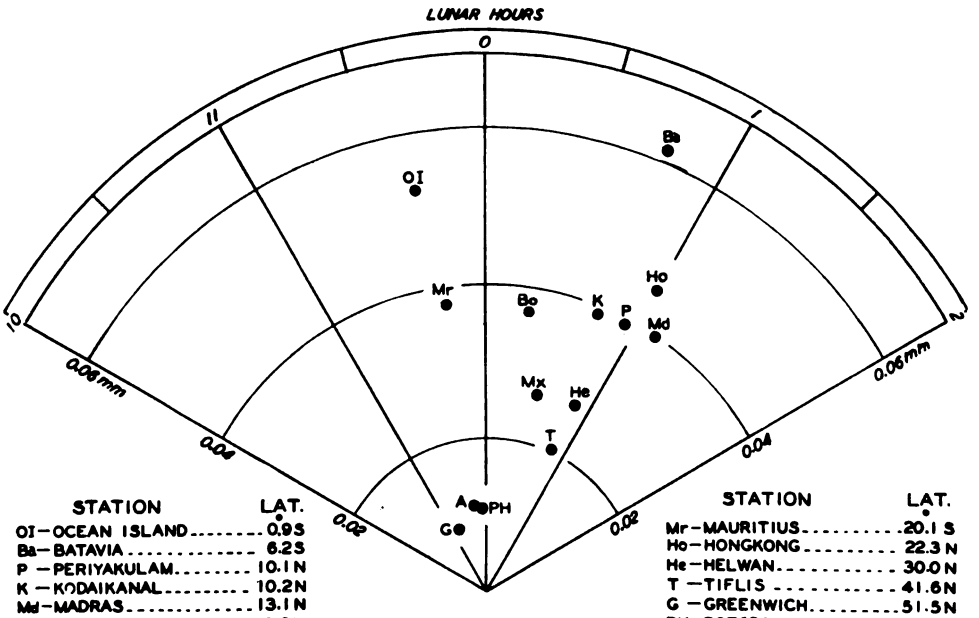


FIG. 23. HARMONIC DIAL FOR THE SEMI-DIURNAL LUNAR WAVE IN PRESSURE AT VARIOUS STATIONS.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

idea is fallacious; not the observational errors but the great natural non-periodic variations of pressure hide the lunar wave. The wave can be found only by refining a great number of barometric curves in which it is so highly diluted.

The principle of these statistical methods is indicated in the harmonic dial for the lunar semi-diurnal waves in pressure at Batavia, Fig. 22. Each of the 40 dots represents the result as computed from the observations in one of the 40 years 1866–1905. The amplitude seems to vary between 0.04 and 0.08 mm, and the highest pressure occurred in some years only about 10 minutes, in others as late as one and a half hours after the transit of the Moon (marked on the dial as O^s). This scattering of the results for the single years is not to be regarded as a real change in the lunar wave from year to year, since it is only due to the difficulty of eliminating the non-lunar variations of pressure from the observations in a single year; but the amount of scattering provides us with a quantitative estimate for the reliability, the probable error, of the average lunar wave as derived from 40 years of observation.

Fig. 23 contains the results of the analyses of lunar waves in atmospheric pressure to date; in all, it represents the extract of over two millions of hourly observations. In spite of the small amplitudes (decreasing from about 0.06 mm at Batavia near the equator to 0.01 mm at Potsdam, and still less at Greenwich), high pressure occurs everywhere within one hour of the lunar transit. The small individual differences in time of the maximum can be attributed to the fact that the atmosphere is not only under the direct influence of the Moon's tidal forces, but is of course secondarily affected by the tidal movements of its under-surface, ocean and land, and the oceanic tides are locally very different, as is well known.

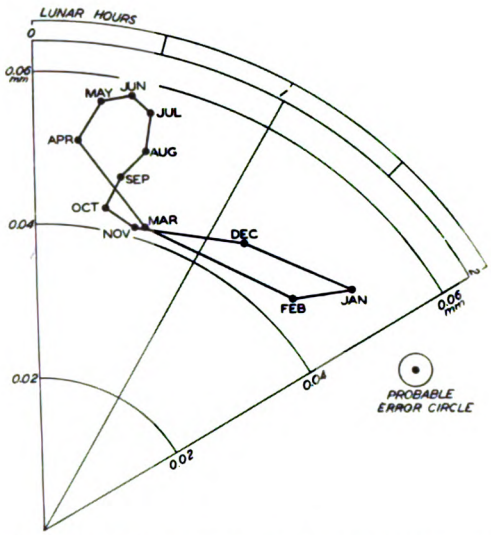


FIG. 24. SEMI-DIURNAL WAVE OF PRESSURE FOR LUNAR HOURS—AVERAGE FOR BATAVIA, BOMBAY, AND HONGKONG.

A puzzling feature of this lunar semi-diurnal wave of pressure of which we just saw the annual averages, is its systematic change in the course of a year, which is surprisingly similar all over the globe. In January, the maximum pressure occurs more than one hour later than in June, and the amplitude is also smaller (Fig. 24). This change is real, because it is far outside the range of the probable-error circles, the size of which is indicated in Fig. 24. Such circles must be imagined to be drawn around

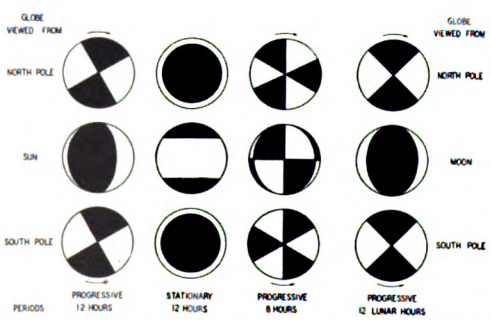


FIG. 25. SCHEME OF WORLD-WIDE OSCILLATIONS OF THE ATMOSPHERE.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

each dot representing a monthly value of the lunar wave in the harmonic dial; they indicate, by their small diameter, the reliability of the monthly values, of which each is based upon about 100,000 hourly values.

The lunar wave in atmospheric pressure is one of those rare cases in which nature makes one simple large-scale experiment at a time. The Moon's heat radiation is negligible, so that the whole effect of the Moon is gravitational, truly tidal. Yet, the rise and fall of the air-pressure with the Moon entails also a slight temperature-variation; because, when air is compressed, it gets warmer. An every-day experience of this is that when air is pumped into a car-tire the valve gets hot. The compression and dilatation of the air in the lunar pressure-wave is so small that even for the tropical station Batavia theory predicts only a so-called adiabatic heating by 0.015 degree Centigrade from the lowest to the highest pressure in the lunar wave. Through the reduction of over 60 years of hourly observations of air-temperature at Batavia, this minute temperature-effect has indeed been found, and one may conclude that here in Washington a similar, though smaller, effect exists. In familiar terms, under like weather conditions, here in Washington it is about one fiftieth of a degree Fahrenheit warmer when the Moon stands highest in the sky or lowest below the horizon than when the Moon rises or sets at the horizon. Of course, the temperature-changes which accompany the weather changes are about one thousand times as large; but the lunar wave gives interesting information about the properties of the atmosphere, because it is the only case in which we can study the effect of a pure pressure-change on large air-masses without the vitiating influence of simultaneous changes in radiation.

The problems with which finally an explanation of the tidal atmospheric movements is faced are best formulated in connection with Fig. 25, which summarizes the results of the observations. It shows for each of the world-wide oscillations of the atmosphere, three schematic views of the globe from the north and south poles and from the Sun or Moon; high- and low-pressure areas are indicated in black and white. The main wave is the 12-hourly progressive solar wave, with maxima at 10 o'clock; it is that which appears clearly on the barograph-curves of tropical stations. The others, which we could obtain only by harmonic analysis of long series of observations, are the small stationary 12-hourly wave (predominant in polar regions), the 8-hourly wave with its contrast between the winter and summer hemisphere, and finally the lunar wave.

The lunar wave is most easily explained, because it has exactly the expected form of the tide produced by the Moon's gravitation. With the same certainty we can say that the 8-hourly wave is not gravitational in origin, because there is no such part in the tidal forces. In fact, it is produced by the 8-hourly wave of temperature, as was suggested by the fact that the 8-hourly waves in pressure and temperature show the same characteristic reversal from summer to winter.

The main solar 12-hourly wave of pressure is complex in nature. It consists of a gravitational part (with maxima about noon and midnight) and a thermal part (with maxima about 8 o'clock) produced by the 12-hourly wave in temperature; the combination of both gives maxima at about 10 o'clock as observed. And the zonal oscillation seems to be connected with the differences of the 12-hourly temperature-waves over land or sea.

These considerations are, however, only qualitatively satisfactory, but seem to fail quantitatively. Because, if the world-wide 8-hourly wave of pressure is produced by the small 8-hourly wave in

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

temperature, why do we not find a large world-wide 24-hourly pressure-wave caused by the large 24-hourly wave of temperature?

The answer may be illustrated by an electrical analogy which is nowadays perhaps more familiar to us than any mechanical analogy, namely, radio reception. For simplicity we consider a simple detector-set without amplifying tubes. Out of the great many electromagnetic oscillatory forces which are sent out by wireless stations and act incessantly on the antenna of this radio receiving set, all are suppressed except those of the period or frequency for which the set happens to be tuned, or, to use another expression, the set responds only to waves which are in resonance with the free oscillation of the set. The atmosphere, as a spherical shell, can perform a great variety of mechanical oscillations, but theory shows that only the kinds of oscillations shown in Fig. 25 are in tune with thermal or gravitational causes. All others, for instance, all the 24-hourly waves are more or less suppressed because of lack of resonance.

The detailed mathematical theory is intricate. Fortunately, for the case of an ocean of uniform depth covering the whole Earth, the tidal oscillations have been discussed by Laplace and Hough. Their formulae did not find any application whatever in that field for which they were derived, namely, in the discussion of the tides in the oceans themselves, because they do not consider the influence of the continents. But it has been possible to transfer their equations to the unlimited air-ocean, and the atmosphere is found to respond to tidal forces like a water-ocean of 5 miles depth.

The solar and lunar semi-diurnal pressure-wave (at the left and right in Fig. 25) have the same form of oscillation, but the lunar wave has a somewhat longer period, or, to use a radio expression, a lower frequenecy. The frequency per year of the solar semi-diurnal wave is, of course, $2 \times 365 = 730$, that is, the peak of the solar semi-diurnal wave passes each station 730 times per year. The frequency of the lunar semi-diurnal wave is only 705 cycles per year. The free oscillation of the atmosphere seems to be about four minutes less than 12 hours, corresponding to a frequency of 734 cycles per year. Now if we have a receiving set tuned to the frequency 734 cycles, and two stations are sending, *S* on the near frequency 730 and *M* on frequency 705, it is clear that station *S* is received with much higher intensity than station *M*, even though *M* may send out higher energy. The application to the oscillations of the atmosphere is evident, though the analogy has of course its limits.

This so-called resonance-theory was first suggested by Lord Kelvin and has been developed by Rayleigh and Margules. Though many difficulties remain, confidence in this theory has recently been strengthened. The theory predicts that an atmosphere that is nearly perfectly tuned in on the progressive solar 12-hourly wave must be also tuned in on the zonal 12-hourly wave and on the 8-hourly wave, and that is exactly what we have found in the observations.

It seems to be more or less fortuitous that the Earth's atmosphere is just so well tuned. If the Earth would lose 10 per cent. of its air, the atmosphere would be tuned in on the lunar semi-diurnal wave, and if it would lose about 30 per cent.—so that the air-pressure at Washington would decrease to the amount which we now observe at an altitude of 10,000 feet above sea-level—none of the world-wide oscillations would be observed at all.

Our survey of the atmospheric tides would not be complete without a brief comparison with similar phenomena. Tidal forces reach enormous amounts when two celestial bodies pass each other

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

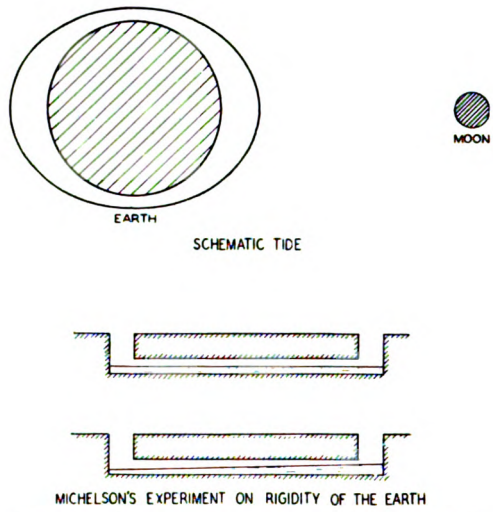


FIG. 26. SCHEMATIC TIDE AND MICHELSON'S EXPERIMENT ON RIGIDITY OF THE EARTH.

at short distance, and the birth of our planet-system has been ascribed to such an encounter of our Sun with another star during which our Sun was not hit by the other star, but broken up under the stress of the gigantic tidal forces. Under present conditions, tidal forces are small on the Earth.

A beautiful experiment of the late Dr. A. A. Michelson has demonstrated the tidal forces and their effect on the solid Earth (Fig. 26). Under the influence of the Moon's tidal forces, an ocean that covered the Earth completely would tend to take the shape illustrated at the top of the figure. Michelson buried underground pipes 500 feet long and filled them half with water. The level of this water would oscillate just as the level of an ocean. Because of the short free oscillation-period of some minutes in such a short pipe the level would adjust itself perfectly to the tidal forces and it is possible to calculate theoretical level-changes from astronomical data. Michelson measured these slight level-changes at the end of the pipe by an ingenious device and compared his observed changes with the theoretical values in order to find whether the solid Earth is perfectly rigid, or whether it is elastic. Because, if the solid Earth itself would yield perfectly to the tidal stresses, then the ground-surface would oscillate just as much as the water, and the observations would give no relative movement of water and ground at all; on the other hand, if the solid Earth were perfectly rigid, the observations would give the full theoretical value. Actually, the observed movements were seven tenths of the theoretical figures, so that the solid Earth yields only to three tenths to the tidal forces. Fig. 27 shows the tidal rise and fall of the water at the south end of a pipe stretching from north to south, for the interval from March 24 to April 21, 1917; the calculated values, which are seven tenths of the theoretical values, agree very well with the observed values. At new Moon, when Sun and Moon are in line, and at full Moon, when Sun and Moon are on opposite sides of the Earth, both pull together and produce maxima exactly at midnight and at noon; at the first and last quarter, Sun and Moon partly neutralize their influence, and the tides are small. The Moon has the greater force; therefore, the maxima occur every day about 50 minutes later.

This famous experiment not only shows the regularity of the tidal forces, but also the astonishing uniformity with which the solid Earth yields partly to the tidal stresses. No selective resonance of any kind disturbs the relation between solar and lunar tides in the solid Earth; both produce effects in the ratio of their forces. In further contrast to the atmospheric tides, no irregular effects are superposed on the minute tidal movements of the solid Earth so that instrumental precision can detect them hour by hour.

This yielding of the solid Earth has also a bearing on the theory of the atmospheric tides, because it demonstrates that the under-surface of the atmosphere

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

is itself in perpetual tidal motion. This is, of course, even more true of the oceans. But the coast-lines hinder the development of a great oceanic tidal wave traveling from east to west around the globe, and the tidal movements of the sea-water are resolved into a number of more or less independent oscillations of the single oceans and smaller gulfs and bays, governed in each individual case by resonance-effects. Nothing demonstrates the complicated nature of the oceanic tides better than the great differences on both ends of the Panama Canal, only about 30 miles apart: On the Pacific side, high and low water are 12 to 16 feet apart, while on the Atlantic side the rise and fall is less than one foot. It is a remarkable demonstration of the good resonance-properties of the atmosphere as a whole that the lunar atmospheric tides are so little affected by the erratic tidal movements of the surface of the oceans.

In comparison with these other tidal phenomena of the solid Earth and the oceans, the tidal oscillations of the atmosphere appear now in some ways more complicated, because they are influenced by the tidal movements of the surface of the continents and oceans, because, furthermore, temperature-variations and perhaps some other meteorological factors act in a similar way as gravitational forces, and because finally the atmospheric tides are hidden by large non-periodic variations; on the other hand, they are more simple because the resonance-properties of the atmosphere as a whole enhance the world-wide oscillations and repress local irregularities. Fig. 28 summarizes the essential features in three schematic spectra. The first shows the gravitational and thermal causes (expressed in equilibrium-values, that is, in terms of theoretical pressure-waves, if the forced periods were much longer than the free periods); the influence of the selective resonance of the atmosphere (shown in the second spectrum) multiplies certain of these causes by high resonance-factors, and suppresses others, which results in the observed oscillations (third spectrum).

It is a fascinating task to disentangle the delicate tidal oscillations of the at-

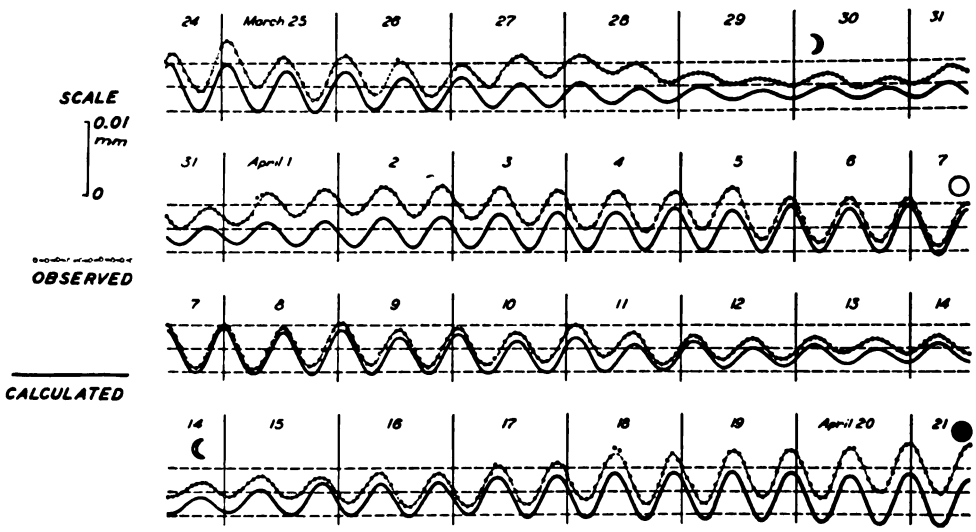


FIG. 27. TIDAL RISE AND FALL OF WATER-LEVEL AT THE END OF UNDERGROUND NORTH-SOUTH PIPE 502 FEET LONG AT YERKES OBSERVATORY (AFTER MICHELSON AND GALE) AS COMPARED WITH COMPUTED VALUES, MARCH 24–APRIL 21, 1917.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

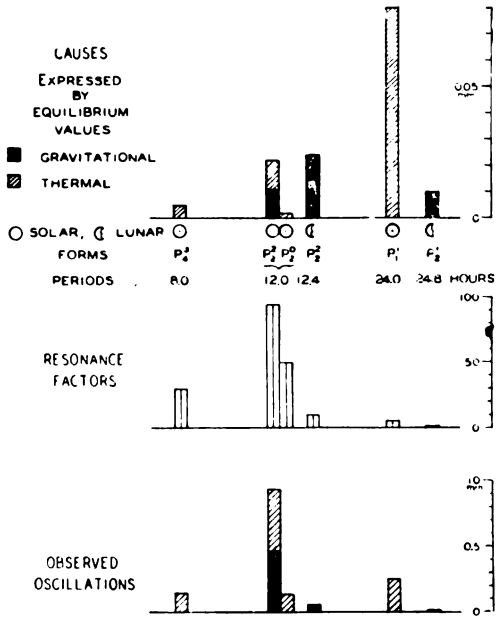


FIG. 28. SCHEMATIC SPECTRUM FOR WORLD-WIDE OSCILLATIONS OF THE ATMOSPHERE.

mosphere from the bewildering irregularities of the daily weather changes. For the weather-forecaster it might appear as a side-track, not worth while pursuing, but do not let us deceive ourselves by apparently practical considerations; those who study these minute phenomena as manifested in the pressure-waves near the ground, or in the magnetic variations as messages from great altitudes, have a similar aim to the physician who is not content to observe the more or less erratic behavior of a man but finds out more about his physical constitution by listening to the beat of his pulse.

Some papers bearing on tides in the atmosphere are:

W. Thomson (Lord Kelvin), "On the Thermodynamic Acceleration of the Earth's Rotation." Edinburgh, *Proc. R. Soc.*, 11, 396–405, 1882.

Lord Rayleigh, "On the Vibrations of an Atmosphere." *Phil. Mag.*, 29, 173–180, 1890.

M. Margules, "Ueber die Schwingungen periodisch erwärmter Luft." Wien, *Sitzber. Ak. Wiss., Math.-naturw. Kl.*, Abt. IIa, 99, 204–227, 1890; 101, 587–626, 1892; 102, 11–56, 1369–1421, 1893.

S. Chapman, "Tides in the Atmosphere." *J. London Math. Soc.*, 7, 68–80, 1932.

S. Chapman, "The World-wide Oscillations of the Atmosphere," *Beitr. Geophysik*, 33, 246–260, 1931.

J. Bartels, "Ueber die atmosphärischen Gezeiten." Berlin, *Abh. Met. Inst.*, 8, Nr. 9, 1–51, 1927. [Abstract in *Naturw.*, 15, 860–865, 1927].

J. Bartels, "Gezeitenschwingungen der Atmosphäre." Wien-Harms, Handbuch der Experimentalphysik, 25, I, 163–210, 1928.

W. J. Bennett, "The Diurnal Variation of Pressure at Washington, D. C." *Mon. Weath. Rev.*, 34, 528–530, 1906.

W. J. Humphreys, "Physics of the Air," 2nd Ed., 1929.

J. von Hann and R. Süring, "Lehrbuch der Meteorologie," 4th ed., 1926.

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero
Digitized by Google
Original from UNIVERSITY OF MINNESOTA

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero

Digitized by Google

Original from
UNIVERSITY OF MINNESOTA

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero

Digitized by Google

Original from
UNIVERSITY OF MINNESOTA

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero

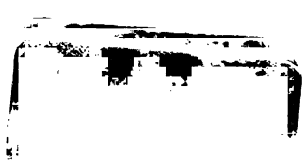
Digitized by Google

Original from
UNIVERSITY OF MINNESOTA

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero

Digitized by Google

Original from
UNIVERSITY OF MINNESOTA



Digitized by Google

Original from
UNIVERSITY OF MINNESOTA

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero

UNIVERSITY OF MINNESOTA
3 1951 P01 105 529 V

Generated on 2025-01-03 10:38 GMT / https://hdl.handle.net/2027/umn.31951p01105529v
Creative Commons Zero (CC0) / http://www.hathitrust.org/access_use#cc-zero

Digitized by Google
Original from
UNIVERSITY OF MINNESOTA